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Assessment of the Durability of Wet Night Visible Pavement Markings: Wet Visibility Project Phase IV

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Final Report VCTIR 12-R13

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Abstract:

This project encompassed a research effort to establish the durability of pavement markings in an on-road installation. Six marking technologies were installed on a portion of Route 460 in Blacksburg, Virginia. A human factors experiment in natural rain conditions was performed to establish the visibility needs of the driver. The retroreflectivity of the markings was measured at intervals of 2 to 5 months, with six measurements over the course of 23 months. The numbers of snow plow crossings and chemical treatments were also measured.

Although all markings lost a considerable amount of retroreflectivity after the first winter, the markings installed in grooves or in rumble strips were shown to retain more retroreflectivity and receive less damage than markings installed on the surface of the roadway. Twenty-three months after installation, the retroreflectivity for all markings in active rain conditions had dropped below the 150 mcd/m^2/lx minimum recommended from previous research. The reflective tape was the closest to maintaining the minimum with a mean retroreflectivity of 137mcd/m^2/lx in 1 in/hr rain. Several other markings maintained a retroreflectivity above 84 mcd/m^2/lx; this may still provide a benefit over standard paint.

The study recommends that VDOT's Traffic Engineering Division install pavement markings in grooves or in rumble strips. VDOT will determine where the use of grooves or rumble strips is appropriate. Because pavement marking visibility is more critical for high-speed roadways such as interstate roadways and major arterials, these roads should be the highest priority. Grooved markings may also be desired for high-volume roadways where markings may be exposed to higher levels of wear from traffic. The study markings on Route 460 in Blacksburg should be monitored for two more years. The study team should make the measurements after each winter through 2013 and report the findings to VDOT in a brief report. VDOT staff should perform additional cost-benefit analyses to address standard VDOT policy, procedures, and practices and possible supplier warranties

FINAL REPORT

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ABSTRACT

This project encompassed a research effort to establish the durability of pavement markings in an on-road installation. Six marking technologies were installed on a portion of Route 460 in Blacksburg, Virginia. A human factors experiment in natural rain conditions was performed to establish the visibility needs of the driver. The retroreflectivity of the markings was measured at intervals of 2 to 5 months, with six measurements over the course of 23 months. The numbers of snow plow crossings and chemical treatments were also measured.

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INTRODUCTION

This is the final project in the Wet Night Visibility Project series performed at the Virginia Tech Transportation Institute (VTTI). The primary objective of the previous projects was to determine the visibility needs of motorists during wet night conditions. These findings were then used to develop performance measures for evaluating wet night retroreflectivity of pavement delineation technologies. However, one critical aspect not considered in this previous research was the durability of the pavement marking materials. Traffic, snow plow operations, and weather all impact the performance of the materials either through damage to the surface, fading, or removal of the retroreflective elements.

The durability of the pavement marking materials is directly related to the life cycle cost of the material, and may be directly related to the initial cost of the material. It is obvious that a material which lasts longer will have to be replaced less often. Knowledge of the material's durability will allow for economic analyses and for the selection of an appropriate material for use in the Commonwealth of Virginia.

PURPOSE AND SCOPE

The purpose of this project was to evaluate the performance and durability of pavement markings in real conditions. The markings were evaluated using measures of retroreflectivity and visibility resulting from human factors experiments. Six materials were tested on a Virginia Department of Transportation (VDOT) test area located on a highway open to the public. The study period was over two winters and the markings were placed on the surface, in a groove and in a rumble strip (two materials).

METHODS

Visibility Experimental Design

This section identifies the experimental design used for this phase of study to measure the visibility of the pavement markings with test subjects driving through the study section. The independent variables are described first. The full factorial experimental design is then presented, followed by a description of the dependent variables.

Independent Variables

Several independent variables were manipulated or controlled for this experiment.

Between-Subjects Variables

- Gender (2 levels): Female, Male. The gender-independent variable was chosen in order to generalize the results of this study to a broad user population. This factor was used for balance only; it was not used in the data analysis.

- Age (2 levels): Younger (18-34 years old) and Older (65 years old and above). The younger and older age groups were selected to investigate the changes in vision and perception that may occur with increasing age.

Within-Subject Variables

- Marking (6 levels): 3M High-build Paint, 3M White Wet-Retroreflective Tape, 3M Thermoplastic, Ennis High-build Paint, Ennis Methyl Methacrylate (MMA), and Epoplex Glomarc 90. These pavement markings were chosen so a wide variety of pavement marking types could be evaluated. The right edge-line and skip lines were tested. All markings were white and 6 inches wide, and each marking section was approximately 900 ft long. A more detailed description of each marking can be found in the Facilities and Equipment section of this report.

- Placement (3 levels): Groove, Surface, and Rumble Strip. The Placement independent variable was chosen to evaluate different installation methods for pavement markings and determine how they affect the performance of the pavement marking. Note that the rumble strips were constructed according to VDOT standards. The groove depth, measured in thousands of an inch (mils), was varied according to the requirements of the marking material suppliers.

Experimental Design Matrix

The full factorial experimental design is shown in Table 1. Originally, six participants from each age and gender group were scheduled to participate. One younger female did not show up at the time of testing, so only five participants from that group were observed. The testing took place on two sides of a divided highway. On two occasions, the required lane closure on one side of the road was not complete at the time testing began, so some participants did not see all conditions (more detail on the lane closure is provided later). Three older males and one older female did not see the markings on the eastbound lanes, and one older female did not see the markings on the westbound lane.

Table 1. Full factorial experimental design matrix.

Pavement Marking	Placement	Older		Younger		Total Observations
		Female	Male	Female	Male	
3M High-Build Paint	Surface	5	2	5	6	18
	Rumble Strip	5	6	5	6	22
	Groove	5	6	5	6	22
3M White Tape	Surface	5	2	5	6	18
	Groove	5	6	5	6	22
3M Thermoplastic	Surface	5	2	5	6	18
	Groove	5	6	5	6	22
Ennis High-Build Paint	Surface	5	2	5	6	18
	Rumble Strip	5	6	5	6	22
Ennis MMA	Surface	5	2	5	6	18
	Groove	5	6	5	6	22
Epoplex Glomarc 90	Surface	5	2	5	6	18
	Groove	5	6	5	6	22

Participants observed each pavement marking in the same order, except for those five participants who only saw markings on one side of the highway. Table 2 shows the order in which markings were seen. The order of the markings was pseudo-randomized for each section of Route 460 to attempt to offset any order effects. However, because the order could not be changed for each participant, some order effects are possibly present in the data. When changing from the eastbound to westbound lanes, participants exited and reentered the highway.

Dependent Variables

Three dependent variables were measured in this investigation.

Detection Distance

As a measure of how visible the pavement markings were, the distance at which participants could see the end of a line was recorded. This was performed by using black roofing material to cover portions of the line, creating the illusion that the pavement markings would come to an end. When a participant could first see the end of a line, they would verbally identify it by saying “Stop” if the line was coming to an end or “Start” if the line was beginning again. The in-vehicle experimenter would press a button when the participant identified a “Stop” or “Start” and again when the vehicle reached that point on the road. These buttons flagged the data so that during later analysis the distance traveled between those two points could be determined. This distance was called the Detection Distance for that particular marking. Figure 1 illustrates this process.

Table 2. Pavement marking presentation order.

Route 460	Pavement Marking	Placement
Eastbound	3M Thermoplastic	Surface
	Ennis MMA	Surface
	Epoplex Glomarc 90	Surface
	3M White Tape	Surface
	3M High-Build Paint	Surface
Westbound	Ennis High-Build Paint	Rumble Strip*
	3M High-Build Paint	Rumble Strip*
	Ennis MMA	Groove (200 mils)
	3M White Tape	Groove (120 mils)
	3M Thermoplastic	Groove (120 mils)
	3M High-Build Paint	Groove (80 mils)
	Epoplex Glomarc 90	Groove (80 mils)

* The skip lines were grooved for these sections. There are two skip line sections with 3M High-Build Paint in a groove.

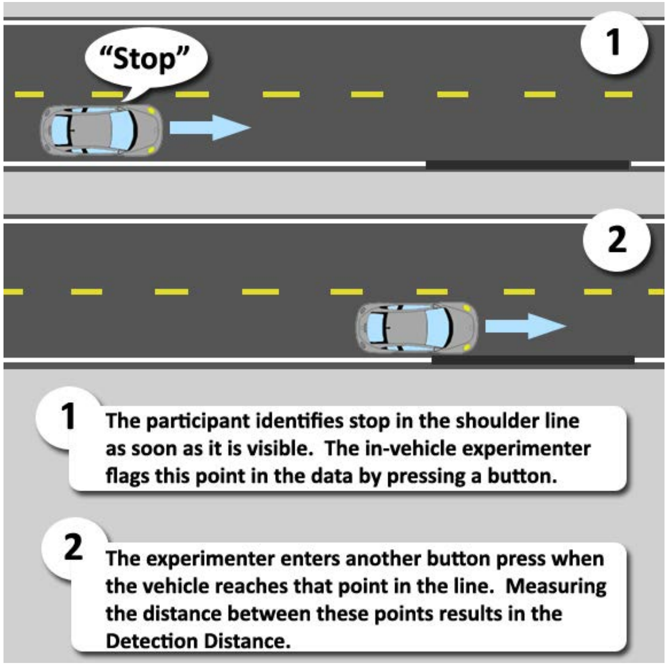

Figure 1. Method for Recording Detection Distance.

Skip Count

As another measure of pavement marking visibility, the number of skip marks (or hash lines) a participant could see was also recorded. For each section of the road with a different type of marking, participants would park in the right lane and count the number of lines they could see while stopped. Participants would tell the experimenter how many lines they could see, and the experimenter would record that number on a note sheet.

Best Edge-line Marking

As a subjective measure of the pavement markings, participants were asked which marking they thought was the best. As participants drove down the road, the in-vehicle experimenter would call out each marking by its section label (e.g., Section A, Section B, etc.). After participants had driven by all eastbound sections (A through E), the experimenter would ask which of those the participant thought was the best. This method was repeated for the westbound sections (F through L). After the participant chose the best marking for both eastbound and westbound lanes, the experimenter would ask the participant to pick which of those two options he or she considered the overall best marking. The participants' answers were recorded by the in-vehicle experimenter on a note sheet.

Participants

Twenty-four participants were selected to take part in this study. One participant did not show up at the time of testing. Participants were selected from two age categories: younger (18-34 years old) and older (65+). Six younger males, six older males, five younger females, and six older females participated. Recruitment occurred through the VTTI participant database and word-of-mouth. A general description of the study was provided to the subjects over the phone before they decided if they were willing to participate. If they were interested, subjects were then screened with a verbal questionnaire to determine whether they were licensed drivers and whether they had any health concerns that should exclude them from participating in the study. If subjects were determined to be eligible for the study, they were then scheduled to come to VTTI for participation. When subjects arrived at VTTI, they read and signed an informed consent form. Subjects were paid $20/hr and were allowed to withdraw at any point in time, with compensation adjusted accordingly.

Facilities and Equipment

Test Road

The experiment took place on Route 460, a four-lane divided arterial, in Blacksburg, Virginia. On an approximately 1.5-mile section between Toms Creek Road and North Main Street, the right lane of the highway was closed to public traffic in each direction during the experiment. Testing occurred on the closed lanes. Figure 2 illustrates how the pavement markings were presented for each test lane. Since the left lane in each direction was open to traffic, there is the possibility that the presence of traffic on the roadway may have influenced some of the visibility measurements. While the experimental timing was established to minimize this impact, a potential conflict exists.

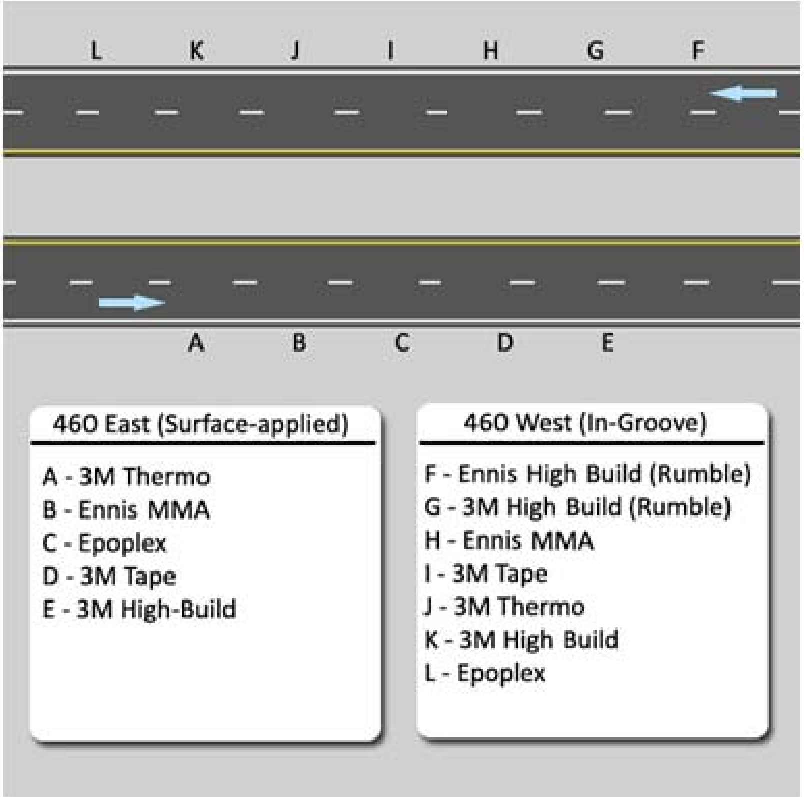

Figure 2. Pavement marking layout on Route 460 in Blacksburg, Virginia.

Test Vehicles

Subjects drove one of two 2003 Chevrolet Malibus (Figure 3) while an in-vehicle experimenter rode in the back seat. The Malibus were equipped with a Data Acquisition System (DAS), which recorded vehicle network data and four camera views inside and around the vehicle. The DAS also recorded button presses entered by the experimenter.

Figure 3. 2003 Chevy Malibu used by participants.

For 14 of the 24 participants, the vehicles were also equipped with a luminance camera developed by VTTI. The luminance cameras took photos as the participants drove the experimental vehicles. The resulting images were later analyzed by an experimenter using proprietary software, which gives the luminance and contrast of the selected part of the image.

For this study, the end point of the edge line at the point the participant detected it was selected for analysis.

Pavement Markings

Six types of pavement markings were tested among three installation methods – surface, groove, and rumble strip – for a total of 12 different conditions. The test pavement markings were installed in May 2009. Table 1 shows the markings listed alphabetically, along with their associated Placements and the sections in which they appeared.

Participants were scheduled in pairs. Upon arrival at VTTI, each participant was asked to read and sign the Informed Consent form and fill out a W9 tax form, a health questionnaire, and a pre-drive questionnaire. Several vision tests were then administered to each participant. A participant's visual acuity was determined using a Snellen chart. A minimum score of 20/40 vision, which is the legal minimum to hold a driver's license in Virginia, was required for further participation. Participants were also tested for contrast sensitivity. Finally, participants were tested for color blindness by indicating what numbers they could see on several pages of a color blindness test. Copies of the informed consent, recruitment materials, and questionnaires are available upon request.

Once all forms and vision tests were completed, an experimenter drove them to a parking lot near the test area on Route 460. There, the participants were escorted to the experimental vehicle they would be driving for the study. The in-vehicle experimenter would familiarize the participant with the vehicle controls (such as seat and mirror adjustments and wiper controls). While the participant got into a comfortable driving position, the in-vehicle experimenter would ensure that the DAS and luminance camera systems were working properly. Once the participant and computer systems were ready, the experimenter would then instruct the participant to exit the parking lot and drive to the test area on Route 460. Participants were told to follow normal traffic laws until they were inside the test lane.

Participants would then drive three loops around the test area. Each loop involved driving from the parking lot on North Main Street to Route 460, through the test lane on eastbound 460, exiting at Toms Creek Road, re-entering westbound 460, turning onto North Main Street, and returning to the parking lot. During the first loop, participants identified points where the line on the right shoulder of the road would either stop or start. This was achieved by using black roofing material to cover portions of the line, creating the illusion that the pavement markings would come to an end.

Participants were shown an illustration to help them visualize what was meant by the line stopping and starting (Figure 4). While the participant drove the first loop, the experimenter flagged the data at the moment the participant identified a Start or a Stop by pressing a handheld button and then flagged the point when the vehicle passed that corresponding part of the line by pressing another button.

Table 1. Pavement marking summary.

Marking	Placement	Section	Image
3M High-Build Paint	Surface Rumble Strip Groove (80 mil)	E G K	
3M Thermoplastic	Surface Groove (120 mil)	A J	
3M Wet-Reflective Tape	Surface Groove (120 mil)	D I	
Ennis High-Build Paint	Rumble Strip	F	
Ennis MMA	Surface Groove (200 mil)	B H	
Epoplex Glomarc 90	Surface Groove (80 mil)	C L	

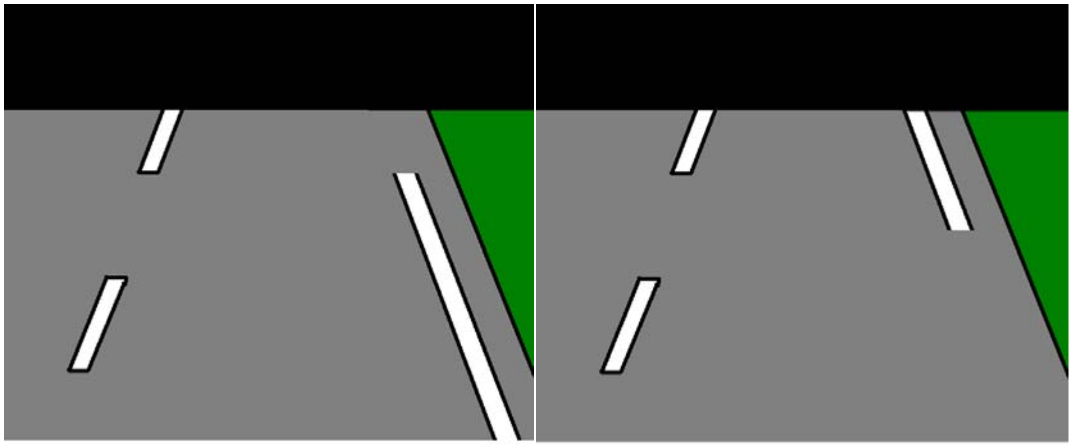

Figure 4. Stop and Start diagrams.

Experimental Protocol

After both participants had completed the first loop, on-road experimenters set up signs at the beginning of each different pavement marking section. The signs showed the designated letter for each section (A through L). For the second loop, participants were instructed to park the vehicle beside the sign for each section and count the number of skip lines that were visible. The participant would tell the experimenter how many lines they could see; the experimenter would then record that number on a note sheet. The experimenter would then instruct the participant to move on to the next sign and repeat the process until all pavement marking sections had been completed.

For the third and final loop, participants were instructed to drive down each test lane and pick which pavement marking they believed to be the best. While driving down the test lane, the in-vehicle experimenter would call out the letter for each section as the vehicle reached them. For example, the experimenter would say, “This is Section A” as the vehicle reached the lettered sign. When the participant had chosen the best marking for each of the test lanes (eastbound and westbound), the in-vehicle experimenter then asked the participant to pick the overall best marking from those two options. The experimenter recorded the participants’ answers on a note sheet.

Once all three loops had been completed, the participant was instructed to return to the parking lot on North Main Street. There, the participants from each experimental vehicle were driven back to VTTI. Pairs of participants were scheduled in such a way that when one group was finished, the next group was ready to begin.

When participants returned to VTTI, they were then given a copy of the informed consent and a receipt showing their time of participation and the amount of compensation they would receive. Participants were mailed a check within two weeks of participation.

The study was conducted during natural rain events on October 27 and November 11, 2009, so that the pavement markings could be evaluated in wet night conditions. Rainfall rates were recorded using a wireless digital rain gauge mounted on a tripod and placed along the side of Route 460. The total rainfall amount was recorded for each lap driven during the course of the experiment. From these data, average rain rates were calculated for each lap. The October session had an average rate of 0.06 inch/hour, with a maximum rate of 0.2 inch/hour. The November session had an average rate of 0.1 inch/hour, and a maximum of 0.33 inch/hour.

Retroreflectivity

In addition to the human subjects experiment, the retroreflectivity of the markings was recorded at different intervals after installation in order to assess each marking's performance over time. Retroreflectivity is the measurement of how much light is returned to a viewer's eyes when looking at an object; in this case, a pavement marking. Retroreflectivity was recorded for four different conditions: dry, recovery (i.e., the "bucket test"), 1 inch per hour of rain, and 2 inches per hour of rain. The retroreflectivity was measured using an LTL-X retroreflectometer, and the rain conditions were created by using a rain box built by VTTI (Figure 5).

Figure 5. VTTI's rain box.

The dry condition was recorded first. The LTL-X was placed on a predetermined location on the marking facing the direction of traffic flow, and three readings were taken. The "bucket test" was performed next by soaking the line in front of the LTL-X with water from a tank in the back of a pickup truck. A hose coming from the tank was held over the line, and water was poured for several seconds in order to ensure coverage of the entire area. After about 45 seconds, three measurements were taken roughly 2 seconds apart. Next, the rain box was placed over the line in front of the LTL-X, and the 1 inch per hour nozzle was turned on. After about 30 seconds, measurements were taken with the LTL-X approximately every 2 seconds until three consistent readings were found. If an inconsistent reading was found (greater than a 10% difference), another set of three measurements would be taken. Those three readings were recorded. The rain box was then switched to the 2 inch per hour nozzle. After another 30 seconds, measurements were taken again approximately every 2 seconds until three consistent readings were found. Those three readings were then recorded. Repeating the measurement was not performed for the bucket test as this test is time-sensitive and the results could be impacted by a time delay.

This process was repeated four times for each marking section; measurements were taken for the edge and skip lines at the beginning and end of each section. The three readings for each condition and each location on a marking were averaged to determine an overall mean for each condition. These tests were performed on six occasions spanning 23 months after the installation of the markings.

Retroreflectivity measurements were taken at four places for each marking segment: approximately 80 feet from the beginning and end of the edge line and at the skip lines nearest those points. These were averaged to create an average edge and an average skip line retroreflectivity for each marking segment.

Project Timeline

The pavement markings were installed in May 2009, and retroreflectivity measurements were taken in August 2009, November 2009, April 2010, September 2010, November 2010, and April 2011. This was conducted to see how retroreflectivity of each marking changed over time due to weathering. In addition, a seasonal analysis was performed. For this analysis, the values from months 3 and 6 were averaged together to create the average pre-winter retroreflectivity for each marking. The values from months 11, 16, and 18 were averaged together to create an average retroreflectivity for each marking after one winter. Lastly, the values from month 23 make up the retroreflectivity for each marking after two winters. The percentage of post-winter data to pre-winter data was calculated to determine the impact of the winter on the retroreflectivity. These data are shown along with the retroreflectivity data for each condition. Figure 6 shows a general timeline of events.

Between the November 2009 and April 2010 readings, Blacksburg experienced an uncommonly harsh winter. The test area of Route 460 was plowed and chemically treated numerous times during several large snow storms. Estimates from the Infrastructure Corporation of America (ICA), which oversaw the plowing process, suggest that the location of the test markings was chemically treated approximately 118 times and plowed approximately 169 times between December 8, 2009, and February 15, 2010. In addition, Annual Average Daily Traffic (AADT) data recorded by VDOT estimated the daily amount of traffic on the test area to be 19,814 in 2009. The winter which occurred between the November 2010 readings and the April 2011 readings was much milder. Estimates from VDOT suggest that the roadway was plowed only 10 to 15 times and chemically treated 15 to 20 times.

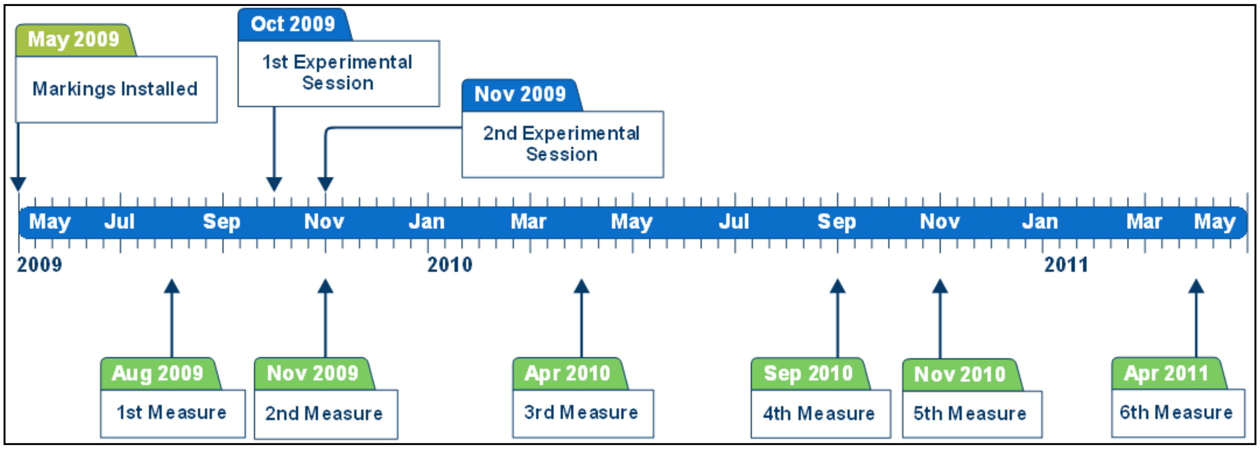

Figure 6. Study timeline.

Luminance Camera Image Analysis

In addition to these methods, an analysis of the luminance camera images was conducted to determine the retroreflectivity of the pavement markings at the moment participants detected a start or stop in the line. Using a custom-made MATLAB program, the luminance of the end point was determined by loading the image which was taken at the moment a participant detected it, and cropping out the end of the marking. This returned a mean luminance for the selected area. Figure 7 shows an example of an image taken from the luminance camera.

Next, the vertical illuminance of the marking was measured. As the data collection activity was from a moving vehicle and measured at the pavement marking there was no means of measuring it during the study and, thus, this value had to be predicted. This was performed by first measuring the vertical illuminance provided by the headlamps of one of the Malibus used in the study. The illuminance at the right edge-line was measured every 25 feet for a range of 25 to 300 feet. These data were used to produce a model for predicting the illuminance based on detection distance. These data were captured in dry conditions. Light would be attenuated due to the transmission of the atmosphere in the rainy condition. However, this impact would also be evident in the testing, so this was not considered in the modeling.. The data and the regression line are shown in Figure 8 along with the associated function and R^2 value.

This provided a predicted level of vertical illuminance, which was adjusted to account for the angle at which participants viewed the markings. The following equation was used to transform the data, in which E_V is the vertical illuminance, *h* is the height of the headlamps, and *d* is the distance to the marking; which, in this case, is detection distance:

$$E_P = E_V / \cos(\tan^{-1}(h/d))$$

Finally, the resulting illuminance value E_P was used with the luminance value attained from the luminance camera image to calculate the retroreflectivity. The following equation was used:

$$Retroreflectivity = Luminance / Illuminance * 1000$$

Figure 7. Luminance camera image.

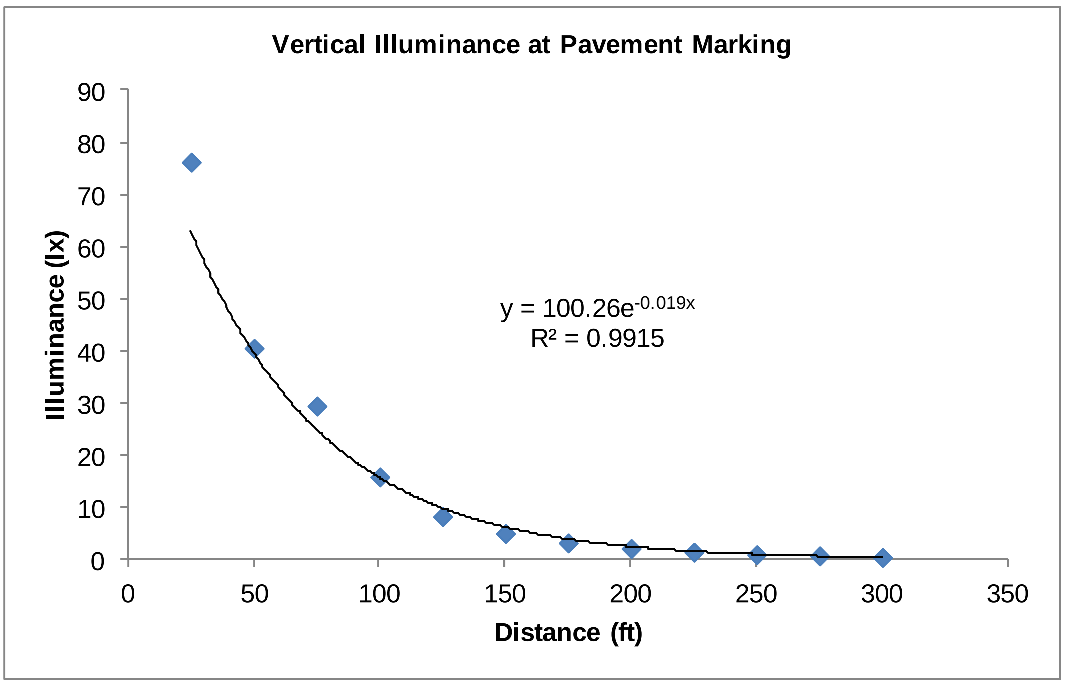

Figure 8. Vertical illuminance at pavement marking.

Uncertainty in Measurements

Several factors may have introduced some uncertainty into the measurements. The first of these factors was the placement of the retroreflectometer on the marking. The location for testing was indicated by a yellow line painted on the shoulder of the road. The experimenter would try to visually line up the front of the retroreflectometer with the yellow line. However, because the line was usually several feet away from the marking, this was not a precise placement. As a result, the retroreflectometer was likely not in the same exact position for each measurement session.

The placement of the retroreflectometer was also affected by damage to the pavement markings. In some instances, portions of the pavement marking had been badly damaged at or near the testing area. To avoid taking measurements that might include portions where the marking had been removed from the road surface, the experimenter would adjust the positioning slightly.

Another factor which may have introduced some uncertainty into the measurements was the method used for measuring the retroreflectivity of markings in rumble strips. According to the ASTM International E1710-05 designation, the correct method is to average several measurements taken over one cycle of the rumble strip. However, because of time constraints, measurements were only taken at the point along the cycle which resulted in the highest values. A rolling lane closure was required to block traffic so that measurements could be taken. The lane closure was only allowed to remain stationary for 15 minutes at a time. Because the retroreflectivity had to be recorded for all four conditions (dry, recovery, 1 in/hr, 2 in/hr) for both the edge and skip lines, only one spot was measured for the rumble strips in order to stay under the 15 minute limit.

Another source for uncertainty was the experimenters themselves. The same two experimenters operated the LTL-X and rain box equipment for the first three measurements (months 3, 6, and 11). One of those experimenters was replaced for the subsequent testing. This may have added some variability to the data as the newer experimenter may have used slightly different methods, such as how much water was used for the “bucket method” test.

In addition to these factors which may have introduced some uncertainty into the measurements across test sessions, another factor led to a loss of data. Between the 11th and 16th months, a majority of the skip lines on the eastbound lanes were mistakenly painted over. For skip line comparisons, several markings (3M Thermo, Ennis MMA, Epoplex, and 3M High-Build Paint all applied on the surface) do not have any data beyond the 11th month due to this.

Data Analysis

For Detection Distance and Skip Count, an analysis of variance (ANOVA) with a significance level of 95% (α=0.05) was used. Because of the nature of the Best Marking variable as a finite number, a simple analysis of frequency was used. Analysis and results of the retroreflectivity data are discussed in the results of the visibility study.

RESULTS

Visibility Study

Edge-line Detection Distance

The first factors considered in these results were those of Age, Marking, and Placement. In this analysis, ANOVA calculations were performed for each combination of factors. This ANOVA was a 2 (Age) x 6 (Marking) x 3 (Placement) mixed factors design. The results from this ANOVA are summarized in Table 4. The significant factors are denoted by an asterisk, and the associated F values are shown.

Table 4. ANOVA results for Detection Distance.

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Sig
Age	1	519595.01	519595.01	7.40	0.0132	*
Marking	5	118578.28	23715.66	7.07	<.0001	*
Age*Marking	5	16760.61	3352.12	1.00	0.4222	
Placement	2	64080.60	32040.30	3.67	0.0359	*
Age*Placement	2	15438.58	7719.29	0.89	0.4219	
Marking*Placement	4	71904.02	17976.00	3.55	0.0128	*
Age*Marking*Placement	4	36206.55	9051.64	1.79	0.1464	
	23	842563.65				
**p* < 0.05 (significant)*						

Within this analysis, Age, Marking, and Placement were all found to be significant main effects. The interaction of Marking and Placement was also found to be significant. Younger participants were able to detect the ends of the lines at significantly further distances (181 ft) than were the older participants (111 ft). This is expected due to the changes in vision associated with aging as an aging eye has a lower contrast sensitivity than a younger one.

Marking was also found to be a significant factor for Detection Distance. Figure 9 shows that the Ennis High-build Paint, 3M High-build Paint, and 3M wet-reflective tape were detected at significantly longer distances than the other markings. The Student Newman-Keuls (SNK) groupings are shown above each bar indicating which pairwise comparisons were not significantly different (those which share same letter), and which pairwise comparisons were significantly different (those with different letters).

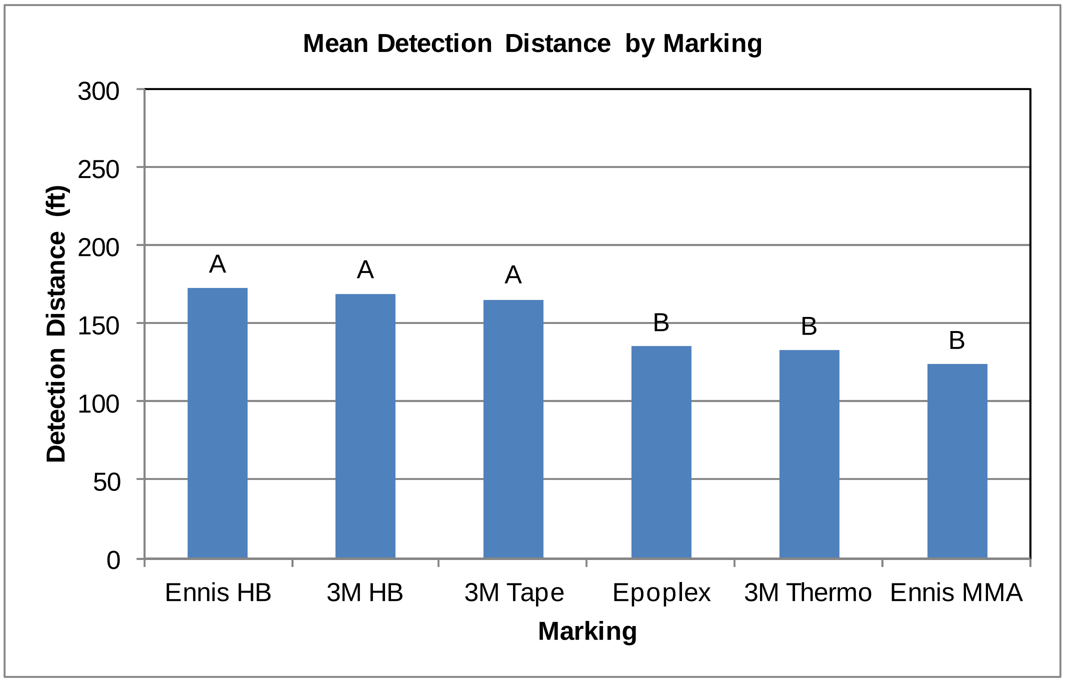

Figure 9. Mean Detection Distance by Marking.

Placement was also found to be significant for Detection Distance in the ANOVA results. Markings installed in a rumble strip were detected at significantly longer distances (177 ft) than grooved or surface-applied markings. There was no significant difference between grooved and surface-applied markings which had means of 147 ft and 142 ft, respectively.

A significant interaction between Marking and Placement was also discovered. Figure 10 shows the mean Detection Distance for each level of Placement and Marking with standard error bars. For most markings, Placement did not cause a significant difference in Detection Distance. For the 3M Thermoplastic and Ennis MMA, however, the grooved line outperformed the surface-applied line. It is important to note that only two markings utilized the rumble strip, and one of those did not utilize any other installation method for comparison. Therefore, only one marking – the 3M High-build Paint – provides a comparison across all Placement types.

In previous Wet Visibility work, a minimum retroreflectivity of 150 mcd/m^2/lx was recommended in order to provide drivers with adequate visibility of the pavement markings (Gibbons and Williams, 2011).

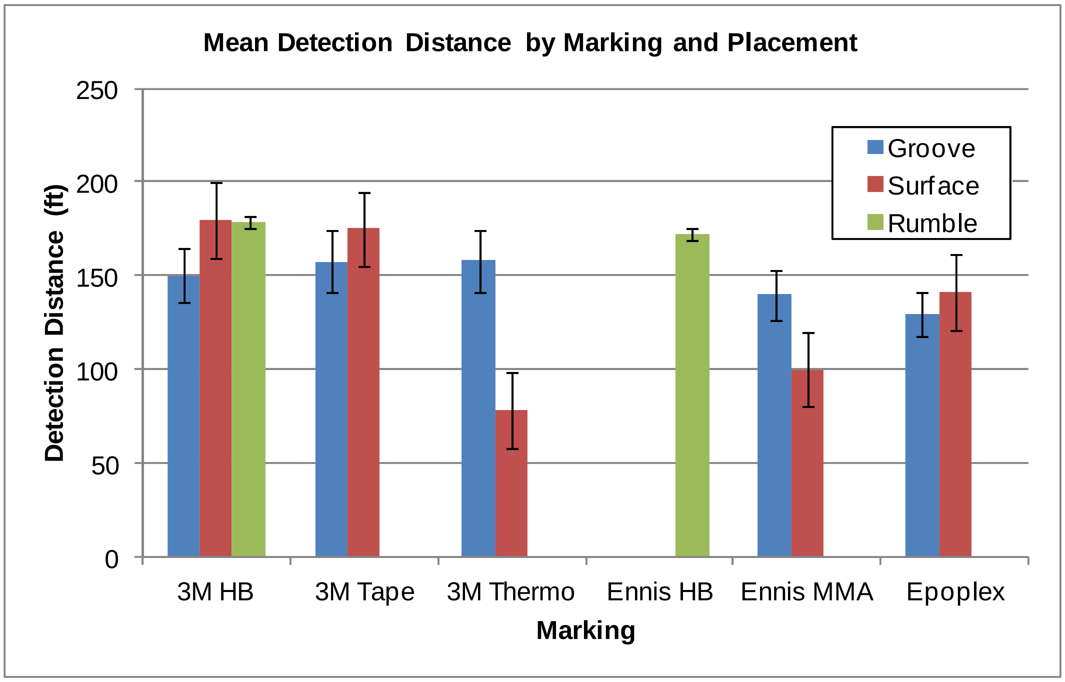

Figure 10. Mean Detection Distance by Marking and Placement.

Figure 11 shows the relationship of detection distance and calculated retroreflectivity, along with the recommended minimum retroreflectivity (dashed line). The data from this experiment seem to support the idea of diminishing returns on retroreflectivity above 150 $mcd/m^2/lx$.

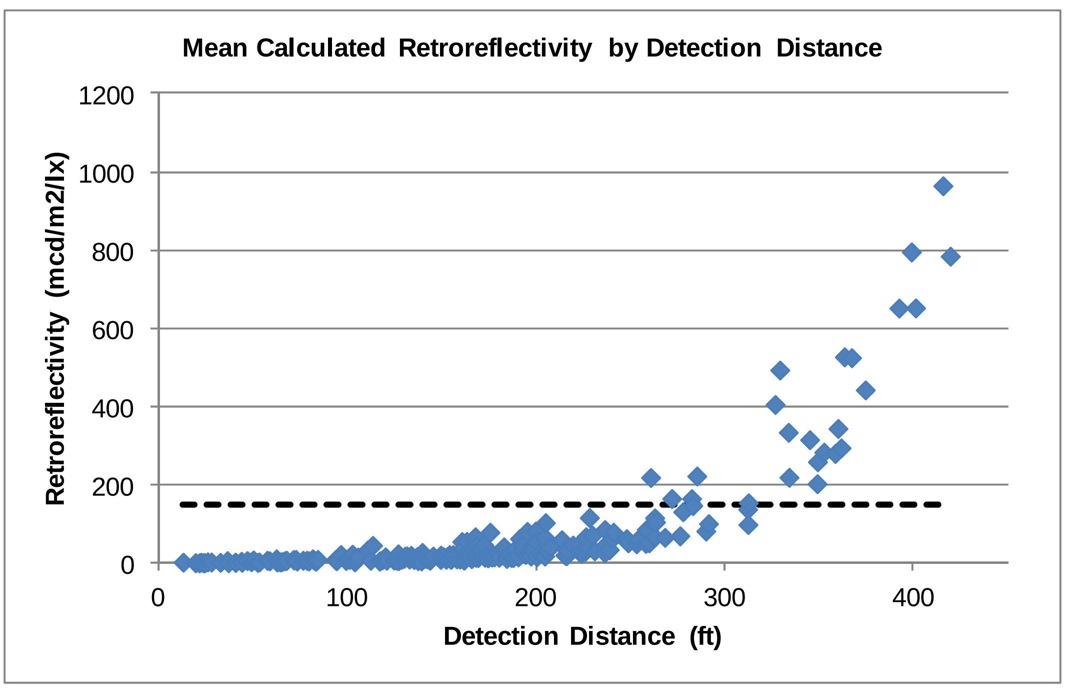

Figure 11. Mean calculated retroreflectivity by Detection Distance.

Skip Count

The ANOVA for Skip Count was a 2 (Age) x 6 (Marking) x 2 (Placement) mixed factors design. Placement only had two levels (groove and surface) in this analysis as rumble strips could not be used for skip marks. The results of the ANOVA are shown in Table 5.

Table 5. ANOVA Results for Skip Count.

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Sig
Age	1	16.18	16.18	2.28	0.1458	
Marking	5	31.03	6.21	8.18	<.0001	*
Age*Marking	5	5.63	1.13	1.48	0.2010	
Placement	1	20.95	20.95	18.18	0.0005	*
Age*Placement	1	0.01	0.01	0.01	0.9234	
Marking*Placement	4	15.68	3.92	7.39	<.0001	*
Age*Marking*Placement	4	1.32	0.33	0.62	0.6471	
	21	90.81				
**p* < 0.05 (significant)*						

Skip Count was significantly affected by Marking. As seen in Figure 12, participants were able to see significantly fewer skip lines for Epoplex Glomarc 90 than was the case for most other Markings. The Ennis MMA was significantly lower than the 3M Tape and 3M Thermoplastic but was not significantly different from any other marking.

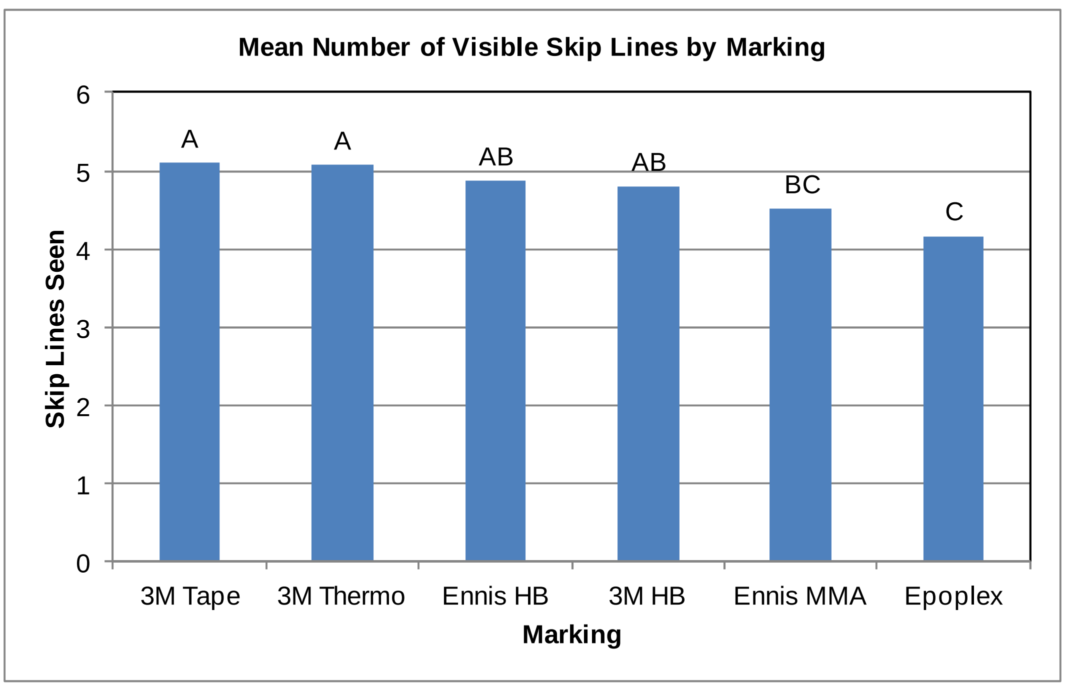

Figure 12. Mean number of visible skip lines by Marking.

Placement was also found to be significant for Skip Count. Markings applied to the surface of the road resulted in significantly more visible skip lines than markings applied in a groove. This difference may not be practically important, however, as the mean number of skip lines seen was 5.1 for surface-applied markings and 4.5 for grooved markings. This may be because surface-applied markings protrude slightly from the roadway, allowing markings at greater distances to be more noticeable.

A significant interaction between Marking and Placement was found for Skip Count. As seen in Figure 13, the 3M Tape, the 3M Thermoplastic, and the Ennis MMA each had significantly higher skip counts when applied to the surface as opposed to in a groove. These three markings also had the deepest grooves (200 mils for the MMA and 120 mils for both the tape and the thermoplastic). This may mean that either the groove depth helped to hide the lines when viewed from a distance or that the thickness of the materials made them more apparent at long distances when applied to the surface.

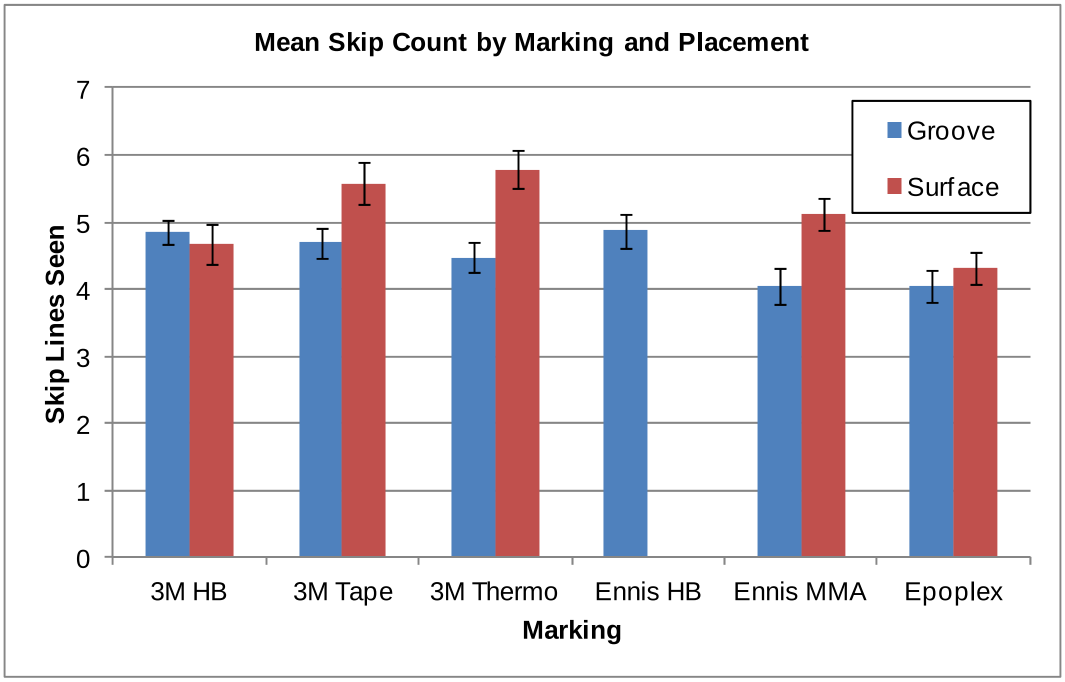

Figure 13. Mean number of visible skip lines by Marking and Placement.

Best Edge-line Marking

Due to the nature of the Best Marking variable, an ANOVA could not be used. Instead, a simple analysis of frequency was used. Best Marking consisted of three parts. Participants would first choose the best marking on the eastbound side of Route 460. They would then choose the best marking on the westbound side of Route 460. Finally, they would choose the overall best marking between those two. Table 6 shows the total number of times a particular marking was chosen. A few participants could not decide which marking they thought was best, and so selected 2 or more markings as equally the best. The markings are shown in the order that they were seen by participants. The type of Placement is also listed. For the surface-applied side of the road, the Epoplex polyurea was chosen as the best marking by 13 participants. For the grooved and rumble-striped markings, the 3M Tape was chosen by nine participants, followed closely by the 3M High-build which was chosen by eight participants. For the overall best marking, the Epoplex polyurea was selected by eight participants. This result is counter to the previously shown results in which several markings were shown to have higher detection distances and skip counts than the Epoplex. It's possible that an order effect may be present, evidenced by the fact that the middle marking for each section was chosen more often than any other marking.

Table 6. Times chosen as the best marking.

Test Bed	Placement	Marking	Best Marking	Overall Best
460 East	Surface	3M Thermo	0	0
		Ennis MMA	1	1
		Epoplex	13	8
		3M Tape	4	3
		3M HB	1	0
460 West	Rumble	Ennis HB	6	2
		3M HB	8	4
	Groove	Ennis MMA	2	1
		3M Tape	9	0
		3M Thermo	0	0
		3M HB	0	0
		Epoplex	1	0

Visibility Study Summary

For Detection Distance, the 3M Tape, 3M High-build Paint, and Ennis High-build Paint generally outperformed the other markings. Markings in rumble strips were detected at significantly longer distances than markings in grooves and on the surface. While no significant difference was found between groove and surface-applied markings in general, it appears to depend on the type of marking as the 3M Thermoplastic and the Ennis MMA both showed significant differences. The relationship of Detection Distance and the calculated retroreflectivity supports previous research which recommends a minimum retroreflectivity of 150 mcd/m^2/lx for the life of the marking. For Skip Count, the 3M Tape and 3M High-build were again among the highest performers, along with the Ennis High-build and 3M Thermoplastic. Though the Epoplex was the lowest performer in terms of Skip Count, the surface-applied Epoplex was subjectively selected as the Best Marking by 42% of participants. The 3M High-build in a rumble strip had the next highest rate of selection with 21%.

Retroreflectivity Analysis Under Wet Conditions

The retroreflectivity analysis sought to answer several questions:

- How does retroreflectivity vary among different types of markings?
- What impact does Placement have on retroreflectivity?
- How does retroreflectivity of a marking change over time?

- How does the retroreflectivity of edge and skip lines differ?
- What impact does winter plowing have on retroreflectivity?
- What is the life of each marking with respect to a 150 mcd/m^2/lx minimum?

To answer these questions, several different analyses were conducted for the retroreflectivity data. Each used an ANOVA with a significance level of 95% ($\alpha = 0.05$). The analyses are listed in the order presented. Because a rainfall rate of 0.8 in/hr is a 95th percentile occurrence in Virginia, the retroreflectivity data collected for the 1 in/hr rain rate were used in these analyses as this most closely matches conditions which drivers are likely to encounter. The analyses used were:

- *Edge-line Analysis:* Due to the missing data for skip lines beyond the 11th month, these analyses only considered edge-line data so that all 23 months of measurements could be included. This analysis sought to answer questions regarding Marking, Placement, and Season.

- *Type Analysis:* Due to the missing data for skip lines beyond the 11th month, these analyses considered only months 3, 6, and 11. This analysis sought to answer questions regarding marking Type (i.e., edge versus skip lines).

- *Durability Analysis:* Data were averaged for each season, which was defined by how many winters the markings had been through: 0 winters, 1 winter, or 2 winters. The percentage of retroreflectivity which was retained after the first and second winter was calculated, and an analysis performed. This analysis sought to answer questions regarding the impact of winter plowing.

Edge-line Analysis

The edge-line analysis looked at edge-line retroreflectivity for 1 in/hr rain conditions across all 23 months of data collection. The results of the ANOVA are shown in Table 7. All factors were found to be significant ($p < 0.05$).

Table 7. ANOVA results for edge-line analysis.

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Sig
Marking	5	733244.177	146648.835	85.08	<.0001	*
Placement	2	334558.516	167279.258	97.05	<.0001	*
Marking*Placement	4	86569.592	21642.398	12.56	<.0001	*
Season	2	1465716.409	732858.205	425.17	<.0001	*
Marking*Season	10	606568.219	60656.822	35.19	<.0001	*
Placement*Season	4	56219.079	14054.77	8.15	<.0001	*
Marking*Placement*Season	8	128048.861	16006.108	9.29	<.0001	*
Total	35	3410924.853				
**p < 0.05 (significant)*						

The significant effect of Marking is shown in Figure 14. The 3M Tape had the highest mean retroreflectivity, and was the only marking to have a mean above the recommended minimum. The 3M High-build was the only other marking to have a mean retroreflectivity near the minimum.

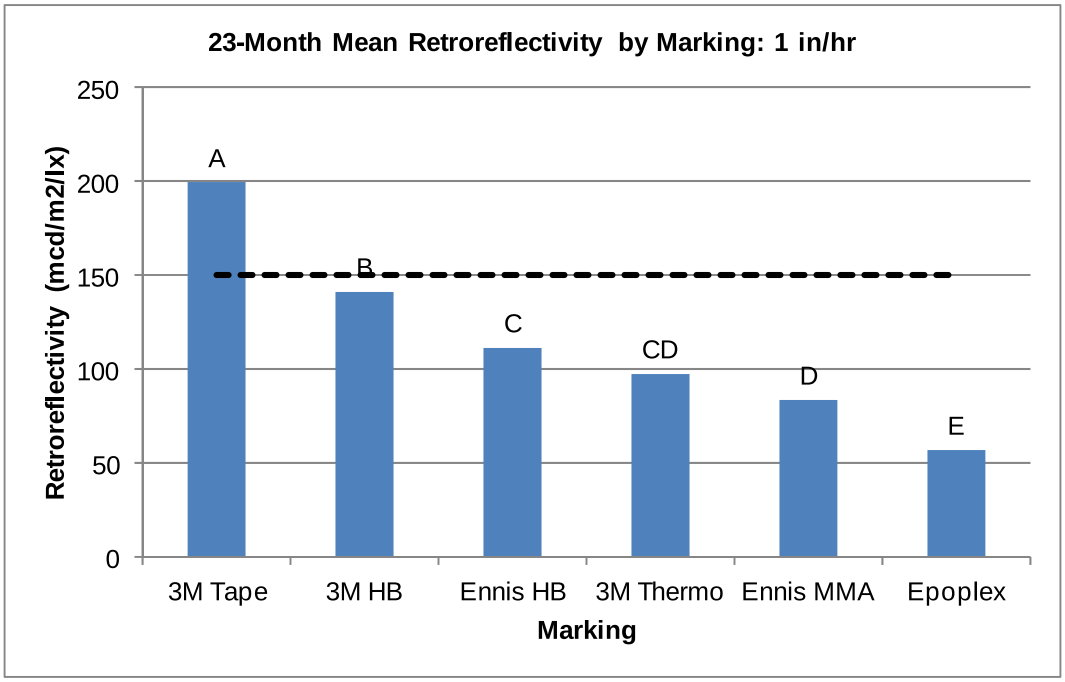

Figure 14. Mean retroreflectivity by Marking for edge-line analysis: 1 in/hr.

Placement was also found to have a significant main effect. Rumble-striped and grooved markings had significantly higher mean retroreflectivities (146 and 143 $mcd/m^2/lx$, respectively) than did surface-applied markings (81 $mcd/m^2/lx$), but were not significantly different from each other.

The significant effect of Season is shown in Figure 15. Season was divided into means for "0 winters" (months 3 and 6), "1 winter" (months 11, 16, and 18), and "2 winters" (month 23). The mean retroreflectivity for all markings dropped far below the minimum after the first winter. Another significant drop in mean retroreflectivity occurred after the second winter; however, this drop was much less severe.

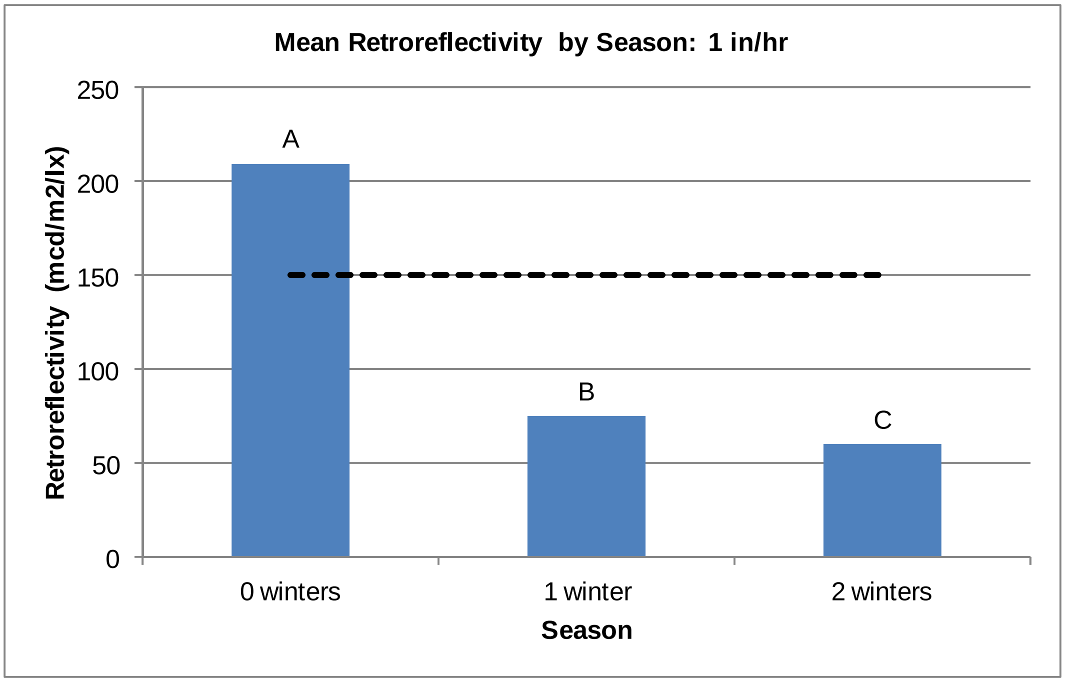

Figure 15. Mean retroreflectivity by Season for edge-line analysis: 1 in/hr.

A significant interaction for Marking and Placement was found. Figure 16 shows that while grooved lines had significantly higher retroreflectivity than surface-applied lines for all markings, the 3M High-build had a larger difference than any other marking. No significant difference was found between the grooved and rumble-striped 3M High-build.

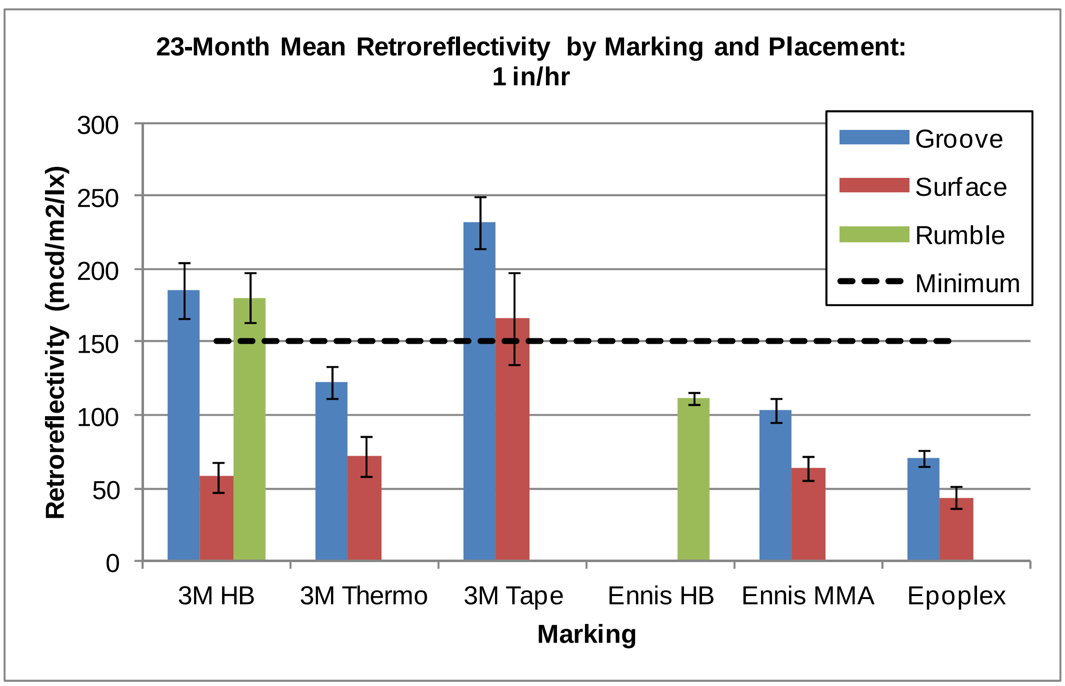

Figure 16. Mean retroreflectivity by Marking and Placement for edge-line analysis: 1 in/hr.

The significant interaction of Marking and Season is shown in Figure 17. The 3M Tape had the highest pre-winter (0 winters) mean, but dropped significantly after the first winter. The Ennis High-build had the smallest reduction in retroreflectivity following the first winter. For the first and second winters, the 3M Tape and the Ennis High-build had the highest means, but were still below the recommended minimum.

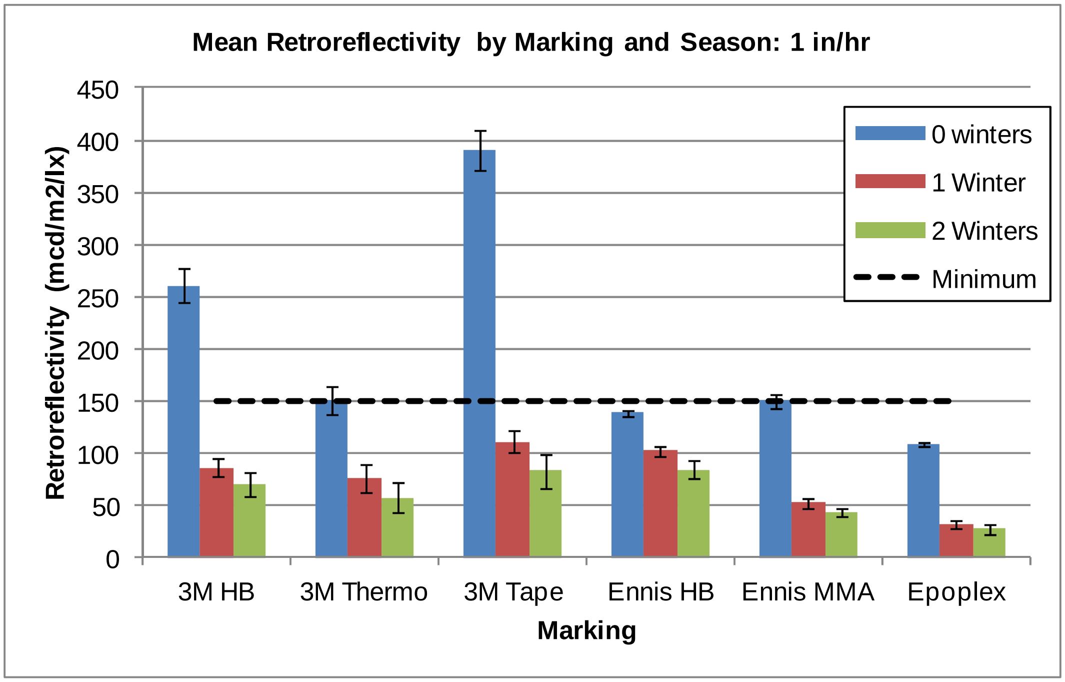

Figure 17. Mean retroreflectivity by Marking and Season for edge-line analysis: 1 in/hr.

Figure 18 shows the significant interaction of Placement and Season. The rumble-striped markings were the only ones not to have a significant decrease in retroreflectivity from one winter to two winters. The increased depth of the rumble strips may have helped protect the markings, especially during the milder second winter. However, it may also be that the two markings in the rumble strips – both high-build paints – were more resistive to wear than the other markings. The surface-applied markings were the most impacted by the first winter.

The significant three-way interaction of Marking, Placement, and Season is shown in Figure 19. The 3M Thermoplastic was the only marking not to have a significant decrease after the first winter for 1 in/hr rain conditions. Markings which did not have a significant decrease in retroreflectivity from one winter to two winters include the rumble-striped 3M High-build, both types of 3M Thermoplastic, the surface-applied Ennis MMA, and the surface-applied Epoplex.

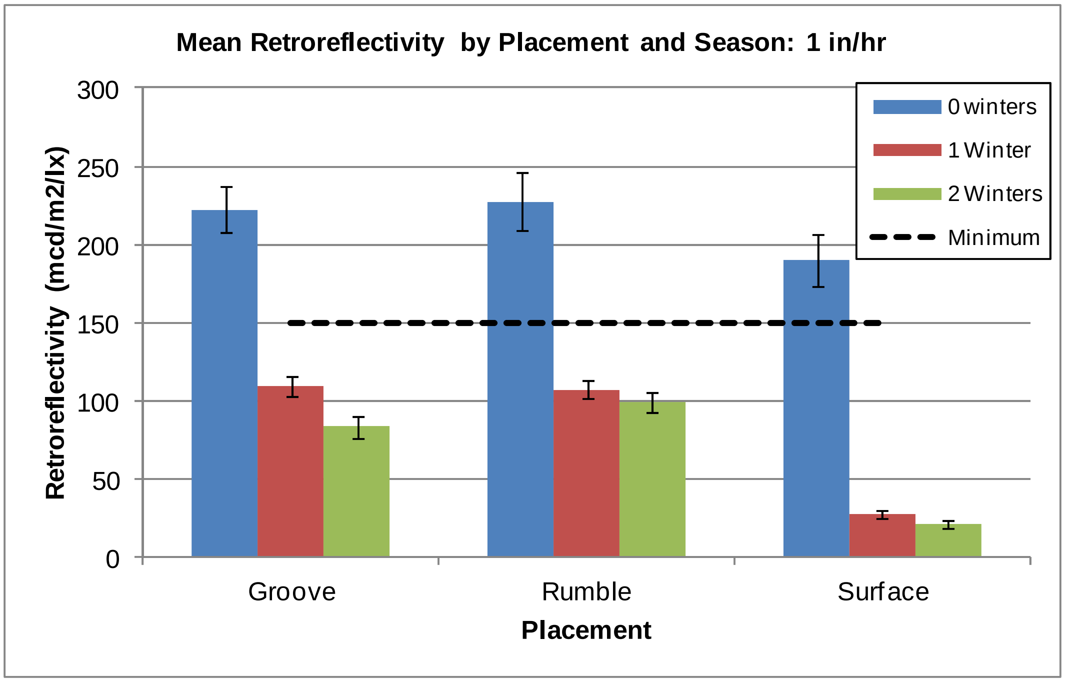

Figure 18. Mean retroreflectivity by Placement and Season for edge-line analysis: 1 in/hr.

For 1 in/hr rain conditions, the grooved 3M Tape was the only marking to have a mean retroreflectivity above the recommended minimum after the first winter. The two markings to have the highest mean retroreflectivity after two winters were the grooved 3M Tape and the rumble-striped 3M High-build, though both were below the minimum.

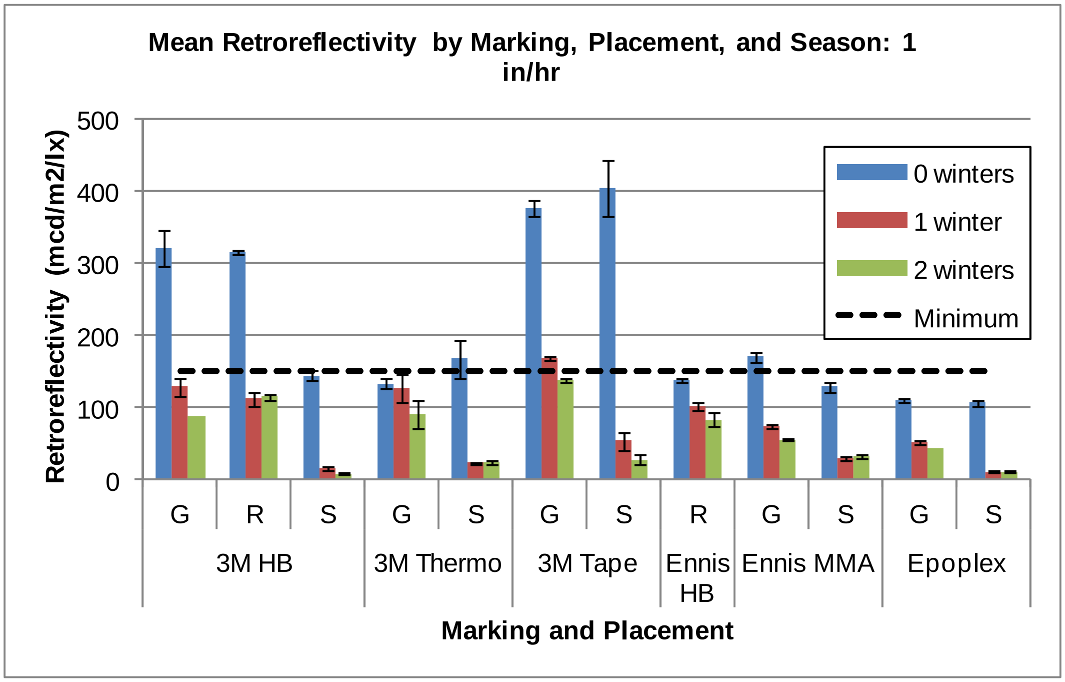

Figure 19. Mean retroreflectivity by Marking, Placement, and Type for edge-line analysis: 1 in/hr.

Type Analysis

The type analysis was performed to identify possible effects of the marking type (i.e., edge line versus skip line). This analysis excluded data beyond the 11th month due to the missing skip line data for that time frame. Only the significant effects of type and its interactions are discussed here. Season was not included in this analysis. The results of the ANOVA are shown in Table 8. Significant factors involving Type are highlighted.

A significant main effect of Type was found for 1 in/hr rain conditions. Edge lines had a mean retroreflectivity of 165 mcd/m^2/lx while skip lines had a mean of 133 mcd/m^2/lx. The mean for skip lines was below the recommended minimum of 150 mcd/m^2/lx.

The interaction of Marking and Type was found to be significant for 1 in/hr rain conditions. Figure 20 shows that while edge lines had significantly higher retroreflectivity for most markings, there was no significant difference for the 3M Thermoplastic or the Ennis MMA.

It is noteworthy that the impacts of the groove versus surface placement did not significantly interact with the performance of the edge-line or the skip-line placement.

Table 8. ANOVA results for type analysis.

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Sig
Marking	5	1402423.863	280484.773	29.21	<.0001	*
Placement	2	161634.095	80817.047	8.42	0.0003	*
Marking*Placement	4	78342.826	19585.707	2.04	0.0881	
Type	1	49457.898	49457.898	5.15	0.0238	*
Marking*Type	4	111595.406	27898.852	2.91	0.0216	*
Placement*Type	1	26965.391	26965.391	2.81	0.0946	
Marking*Placement*Type	4	86753.656	21688.414	2.26	0.0622	
Total	21	1917173.135				
**p < 0.05 (significant)*						

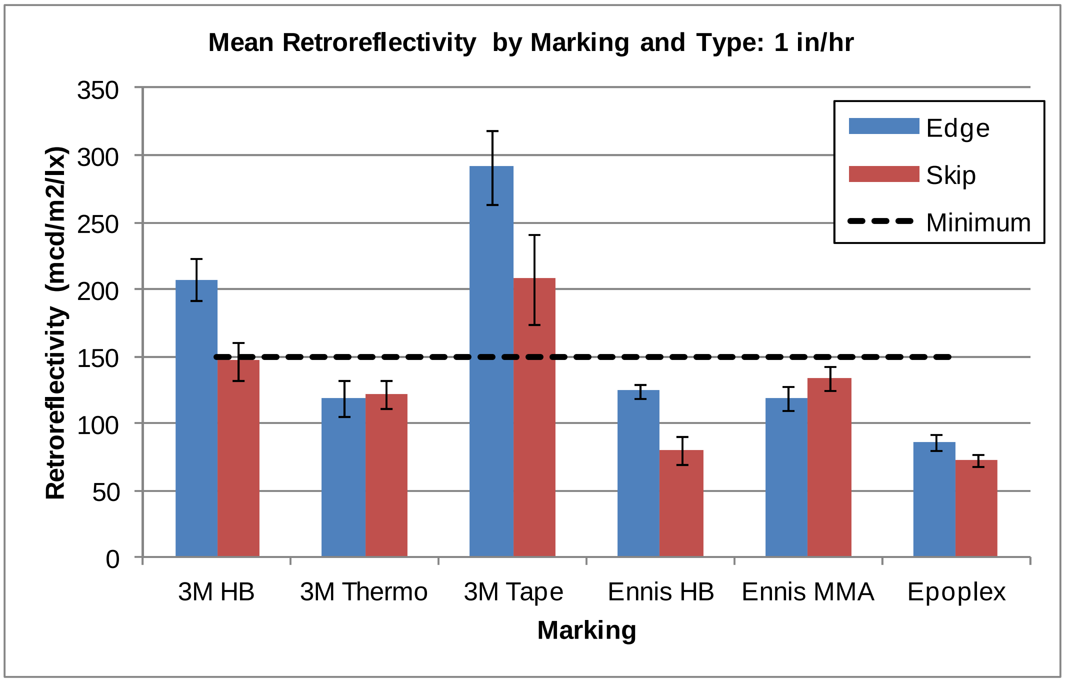

Figure 20. Mean retroreflectivity by Marking and Type for type analysis: 1 in/hr.

Seasonal Analysis

As an assessment of marking durability, the seasonal analysis used edge-line data from all 23 months of data collection to determine the percentage of retroreflectivity that was retained after each winter. Values are shown as a percentage of the pre-winter (0 winters) mean. Only the 1 in/hr rain conditions were used for this analysis. Two ANOVAs were performed; one which looked at the change after one winter, and another which looked at the change after two winters. The results of the seasonal analysis ANOVAs are summarized in Table 9. All factors were significant ($p < 0.05$).

Table 9. ANOVA results for seasonal analysis.

Source	From 0 to 1 Winter		From 0 to 2 Winters	
	F Value	Pr > F	F Value	Pr > F
Marking	18.91	<.0001	34.59	<.0001
Placement	80.54	<.0001	164.04	<.0001
Marking*Placement	8.77	<.0001	12.46	<.0001

Seasonal Analysis: One Winter

Figure 21 shows the significant effect of Marking. After one winter, the Ennis High-build retained the highest percentage of retroreflectivity (75%) followed by the 3M Thermoplastic (58%). The remaining markings had similar rates of retained retroreflectivity ranging between 29% and 34%.

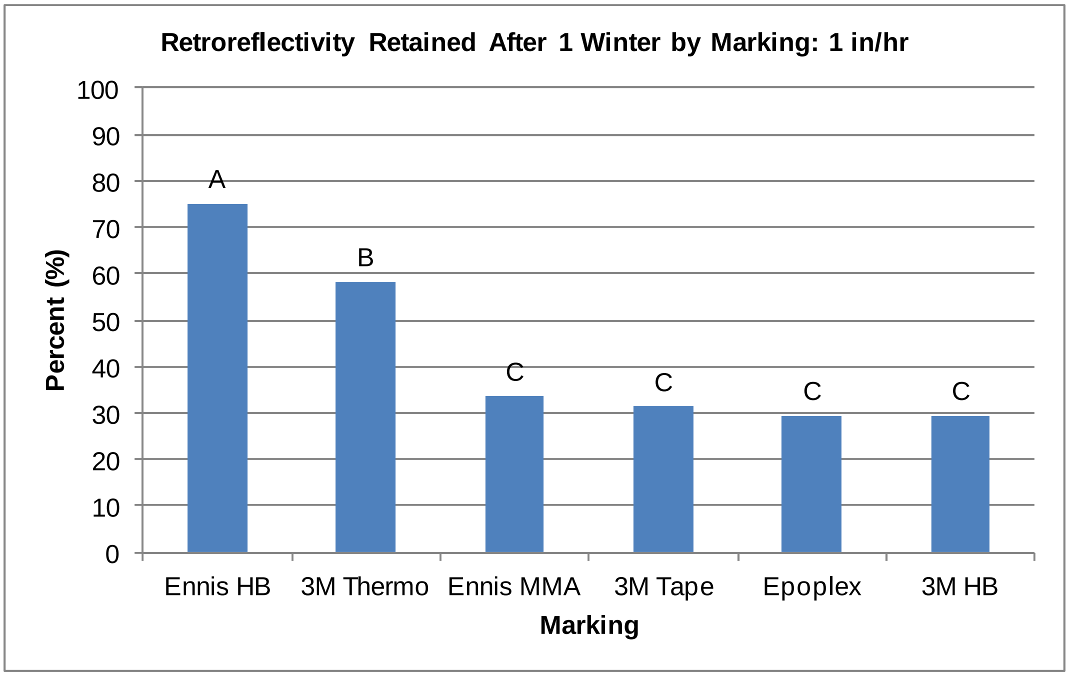

Figure 21. Retained retroreflectivity by Marking after one winter.

The significant effect of Placement is shown in Figure 22. The rumble-striped and grooved markings retained a similar percentage of retroreflectivity (55%), while the surface-applied markings only retained 17% of their retroreflectivity.

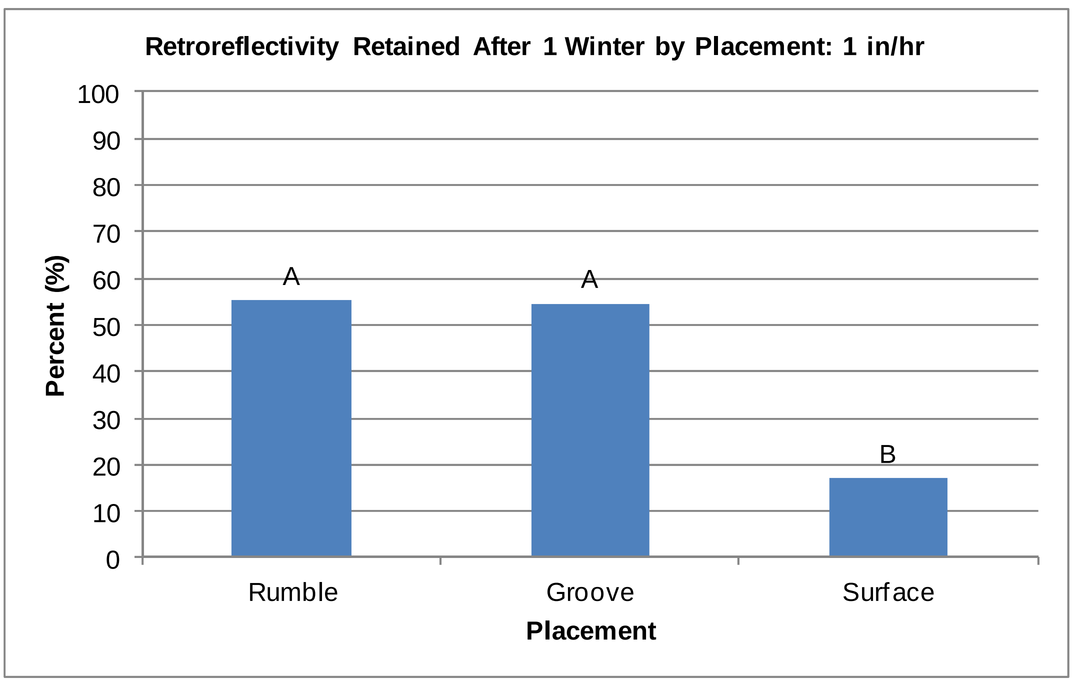

Figure 22. Retained retroreflectivity by Placement after one winter.

Figure 23 shows the significant interaction of Marking and Placement. The grooved 3M Thermoplastic had the highest rate of retention with 94%, followed by the rumble-striped Ennis High-build which retained 75% of its retroreflectivity. For all markings, grooved lines retained significantly higher percentages of retroreflectivity than did their surface-applied counterparts.

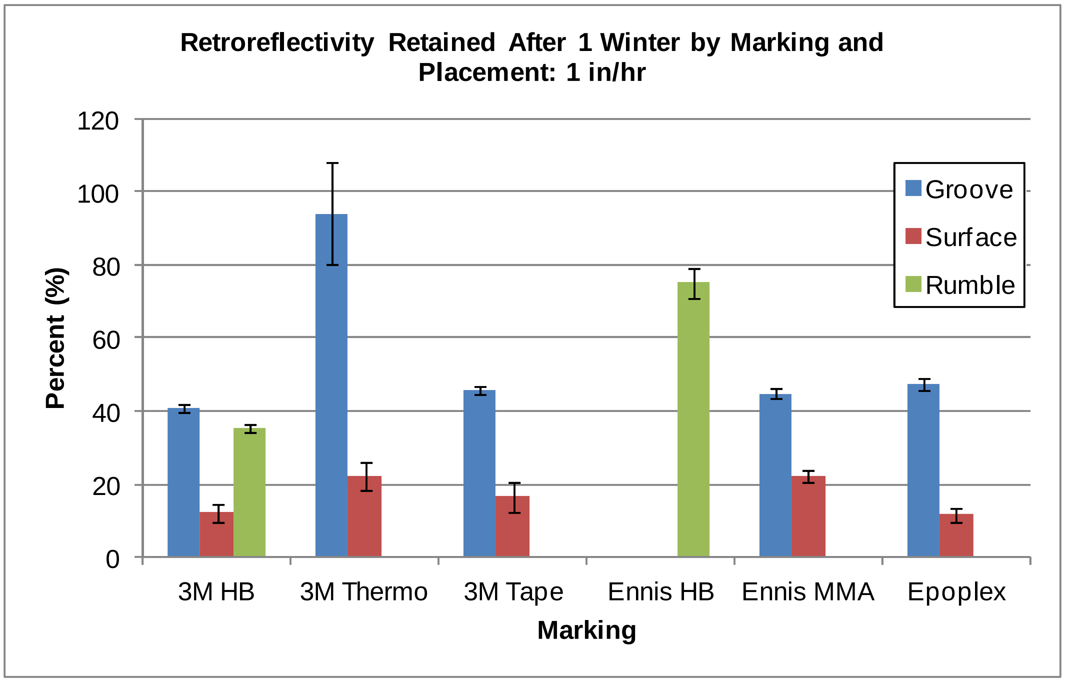

Figure 23. Retained retroreflectivity by Marking and Placement after one winter.

Seasonal Analysis: Two Winters

Figure 24 shows the significant effect of Marking. After two winters, the Ennis High-build still retained a significantly higher percentage of retroreflectivity with 61%, followed by the 3M Thermoplastic with 45%. The remaining markings retained similar percentages which ranged from 23% to 29%.

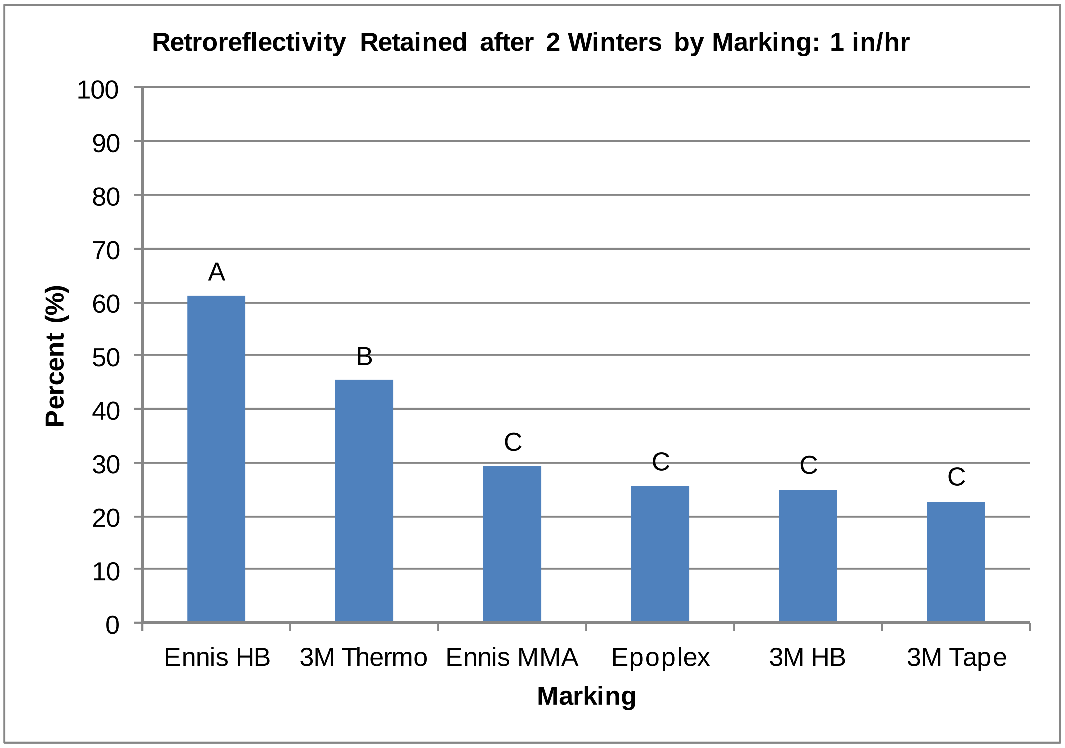

Figure 24. Retained retroreflectivity by Marking after two winters.

Figure 25 shows the significant effect of Placement. After two winters, the rumble-striped markings had retained a higher percentage of their retroreflectivity (49%) than did the grooved (42%) or surface-applied (15%) markings.

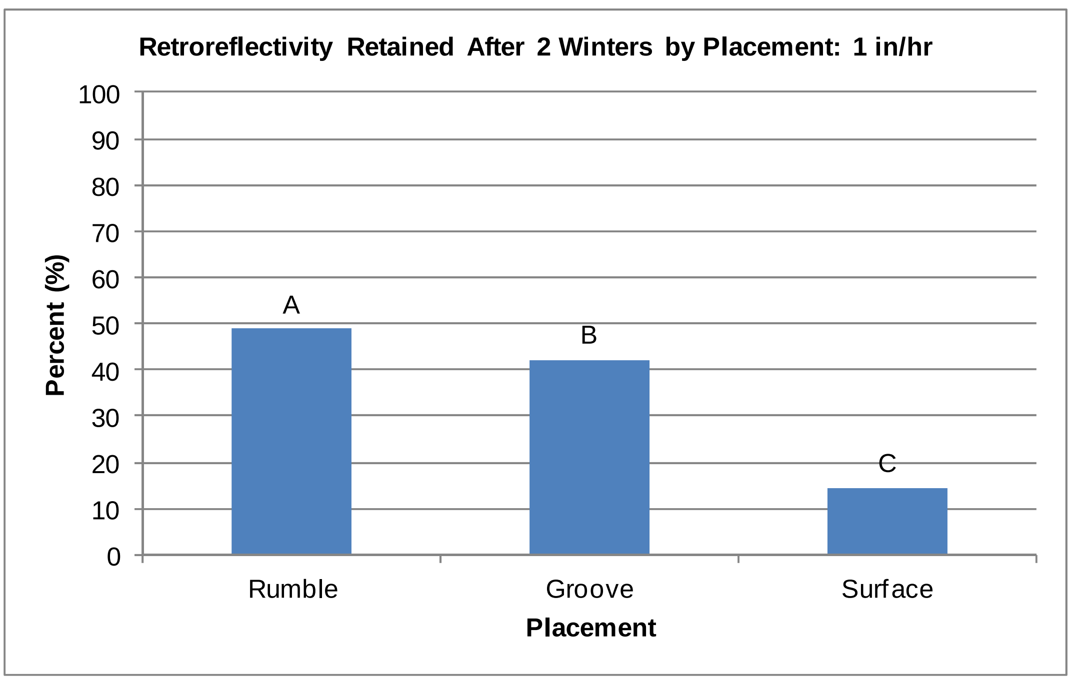

Figure 25. Retained retroreflectivity by Placement after two winters.

The significant interaction of Marking and Placement is shown in Figure 26. After two winters, there was no significant difference between the retained retroreflectivity of the grooved 3M Thermoplastic and the rumble-striped Ennis High-build (68% and 61%, respectively), which had the highest percentages.

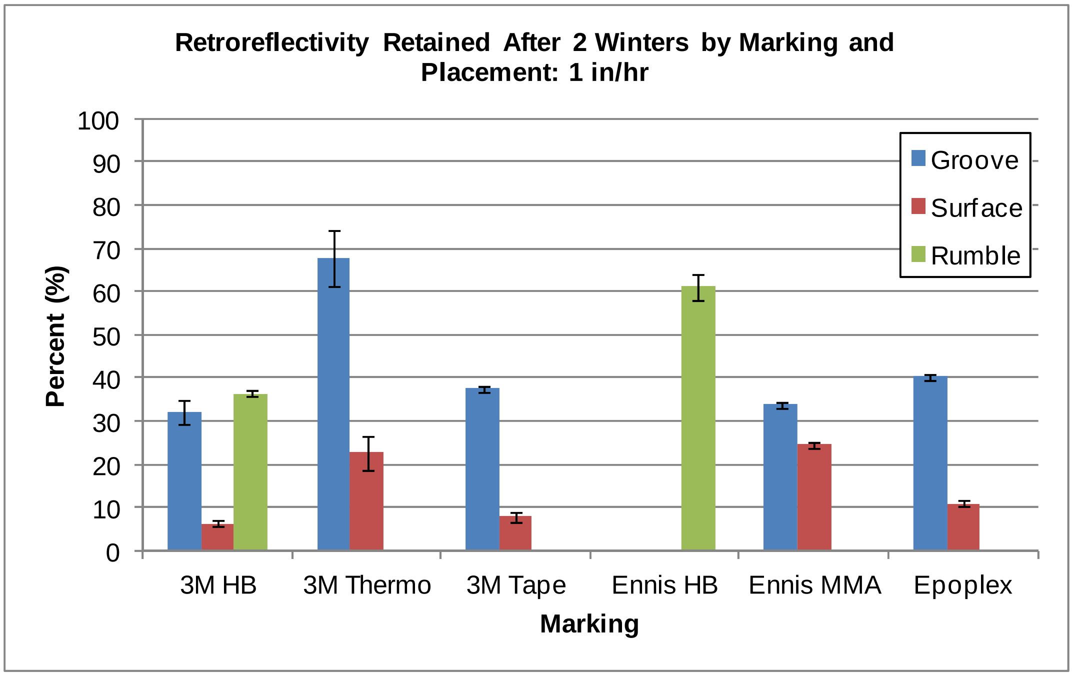

Figure 26. Retained retroreflectivity by Marking and Placement after two winters.

Retroreflectivity Analysis Under Dry Pavement Conditions

Although the focus of this study was the performance of pavement markings in wet conditions, it was also important to determine how each marking performed in dry conditions as that is how drivers will most often encounter them. Figure 27 shows the mean dry retroreflectivity for each marking by Placement and Season. As shown, the mean retroreflectivity for each marking was above the recommended minimum even after 2 winters. The grooved lines had significantly higher means than their surface-applied counterparts, except for the Ennis MMA and Epoplex polyurea.

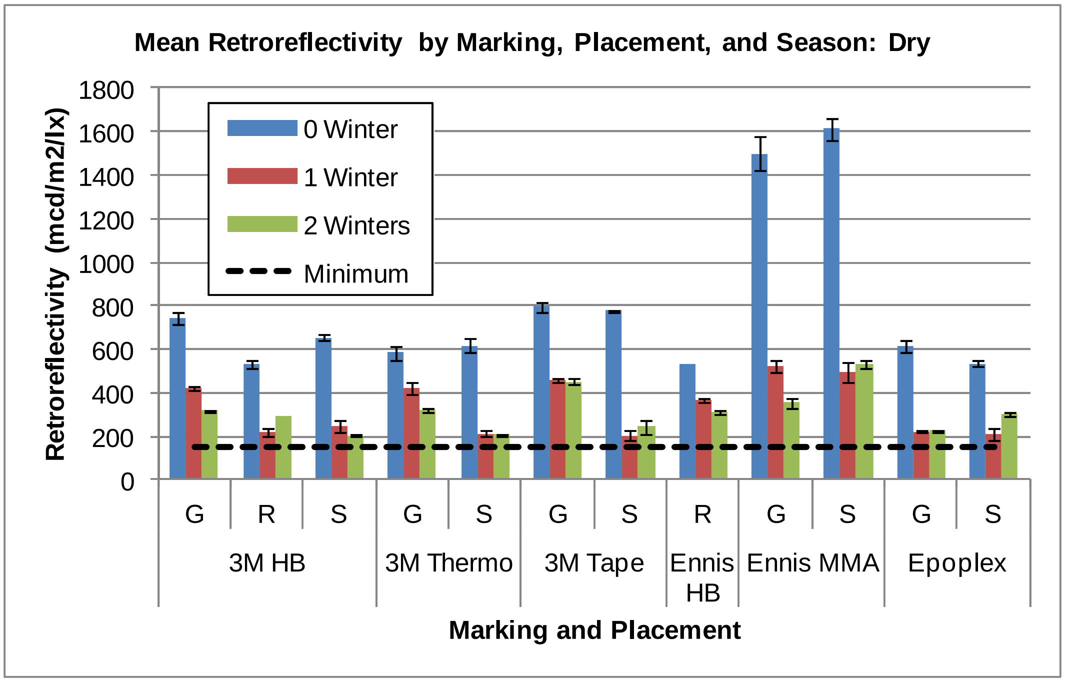

Figure 27. Mean retroreflectivity by Marking, Placement, and Season for dry conditions.

Presence

As another method of evaluating the durability of the markings, photos of the markings taken during the 23rd month were analyzed to determine how much of the pavement marking remained on the surface of the roadway. This measure was called Presence. A special MATLAB program was written which converted the photos into black and white images. A box was then drawn around the pavement marking, and the percentage of white pixels in the box was given. Between two and seven photos were used for each Marking and Placement combination, so this measure does not represent the state of the entire marking, but nevertheless provides some useful information. Photos were taken near each of the measurement locations, and at any prominently damaged areas. Figure 28 shows a black and white image with the box drawn around the pavement marking. The large black areas indicate places where the marking has been removed.

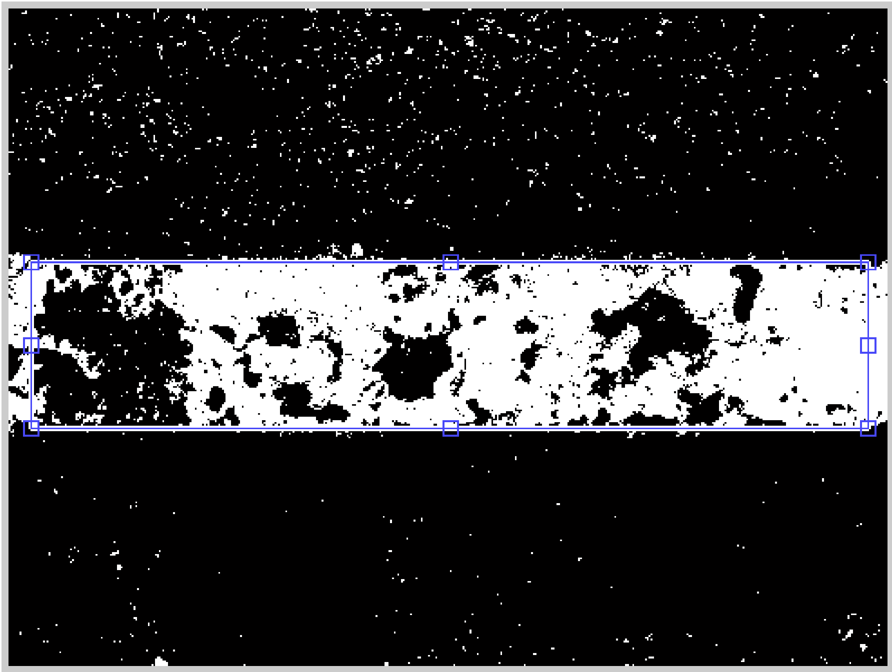

Figure 28. Example image of Presence measurement.

Figure 29 shows the mean Presence for each Marking and Placement. As shown, the grooved 3M High-build, 3M Tape, and Epoplex had Presence of over 90%. The Ennis MMA had the lowest presence for both grooved and surface-applied markings; however, this is likely due to the nature of the marking as it does not completely cover the road surface. The two rumble-striped markings also had low Presence as the "crowns" of the rumble strips were exposed and received heavy damage.

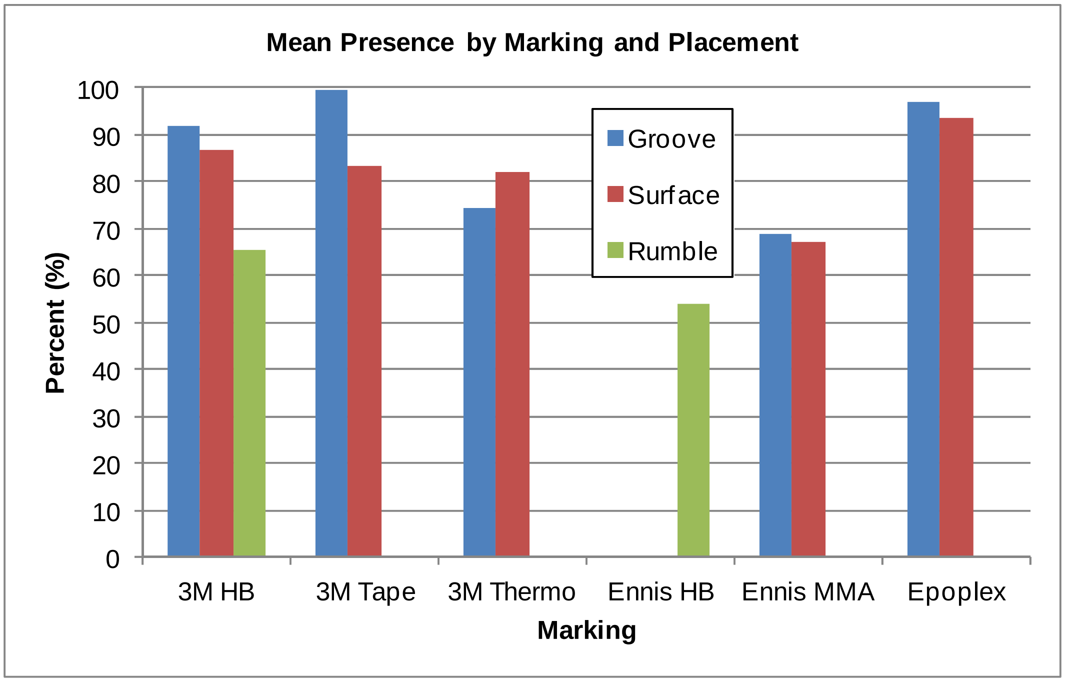

Figure 29. Mean Presence by Marking and Placement.

Figure 30 shows the minimum Presence for each Marking and Placement, which would indicate a small area which received the worst damage. The grooved 3M High-build, 3M Tape, and Epoplex still had very high presence. The 3M Thermoplastic and the surface-applied 3M Tape had the biggest drops in presence when compared to the mean. This was due to areas where heavy damage had removed large chunks of the marking from the roadway.

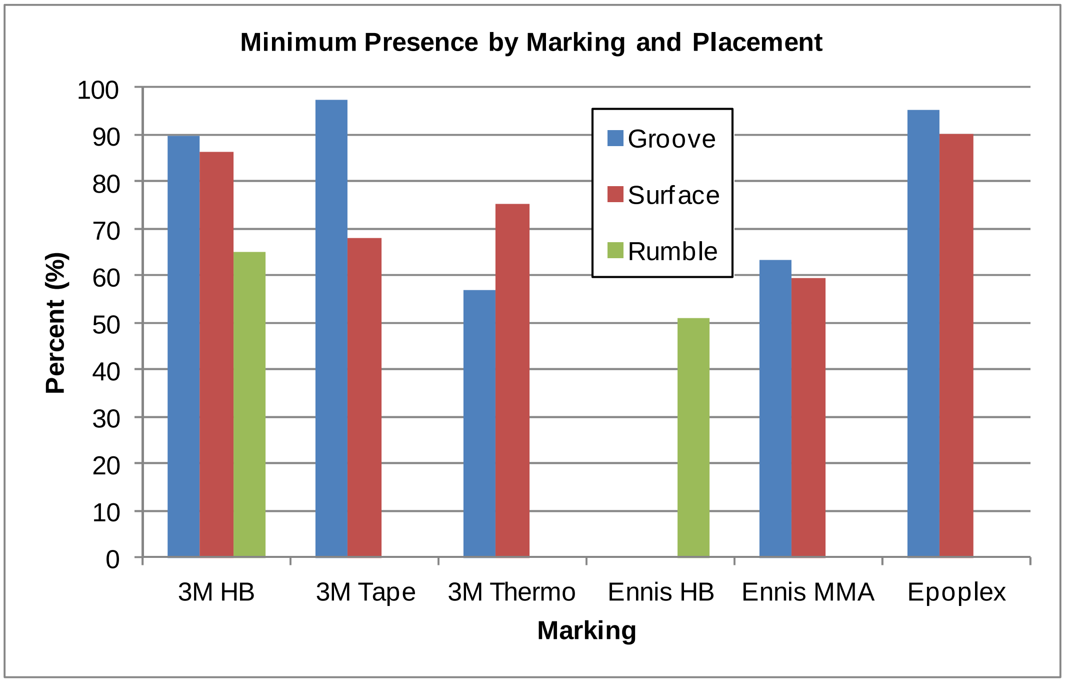

Figure 30. Minimum Presence by Marking and Placement.

Lifetime Analysis

Using the retroreflectivity data, an estimate of each marking's lifetime with respect to the recommended minimum of 150 mcd/m^2/lx was established. This was accomplished by plotting a line graph of the retroreflectivity over time, and finding the point at which the line crossed below the minimum. Figures 31 and 32 show examples of such plots for the 1 in/hr and dry conditions respectively. As in Figure 32, the dry retroreflectivity for all but one marking never fell below the minimum within the 23-month test period. Only the surface-applied 3M Tape skip line fell below the minimum.. Table 10 shows the estimated lifetime of each marking based on the recommended minimum retroreflectivity. Blank cells indicate markings that had not fallen below the minimum at the time of the last measurement (23 months). Markings which had already fallen below the minimum when the first measurement was taken (3 months) are marked as taking 3 months since no prior data existed. Cells marked as "NA" indicate where there was insufficient data to make an estimate (i.e., missing skip line data). The bolded cells indicate the marking with the longest estimated lifetime for each of the wet conditions.

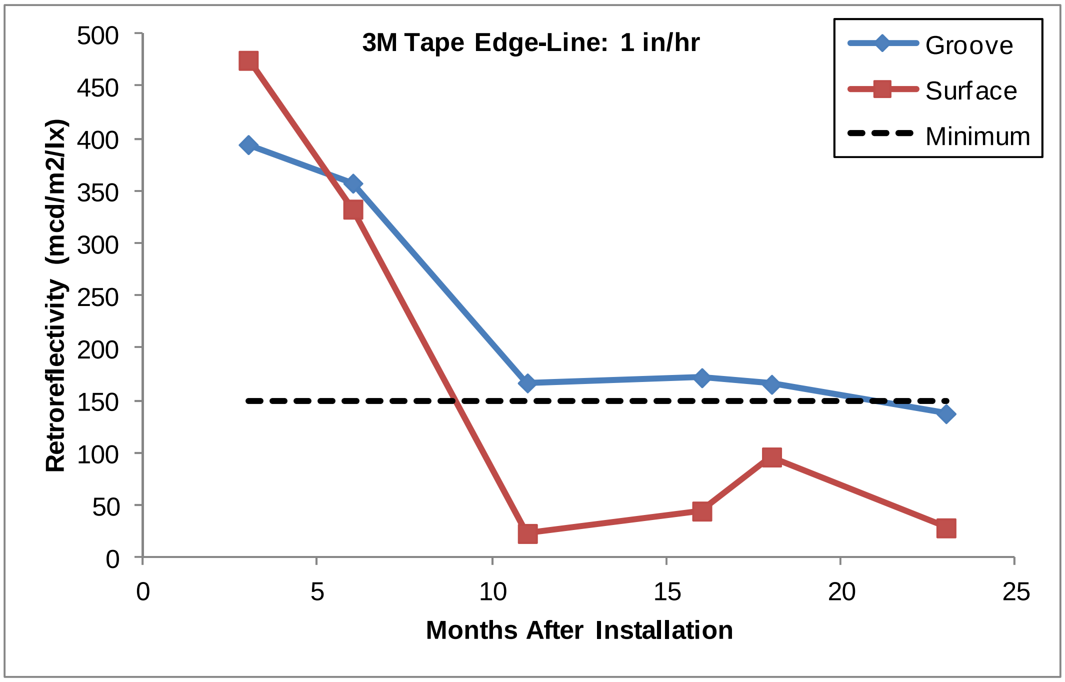

Figure 31. An example of a time plot used to estimate lifetime.

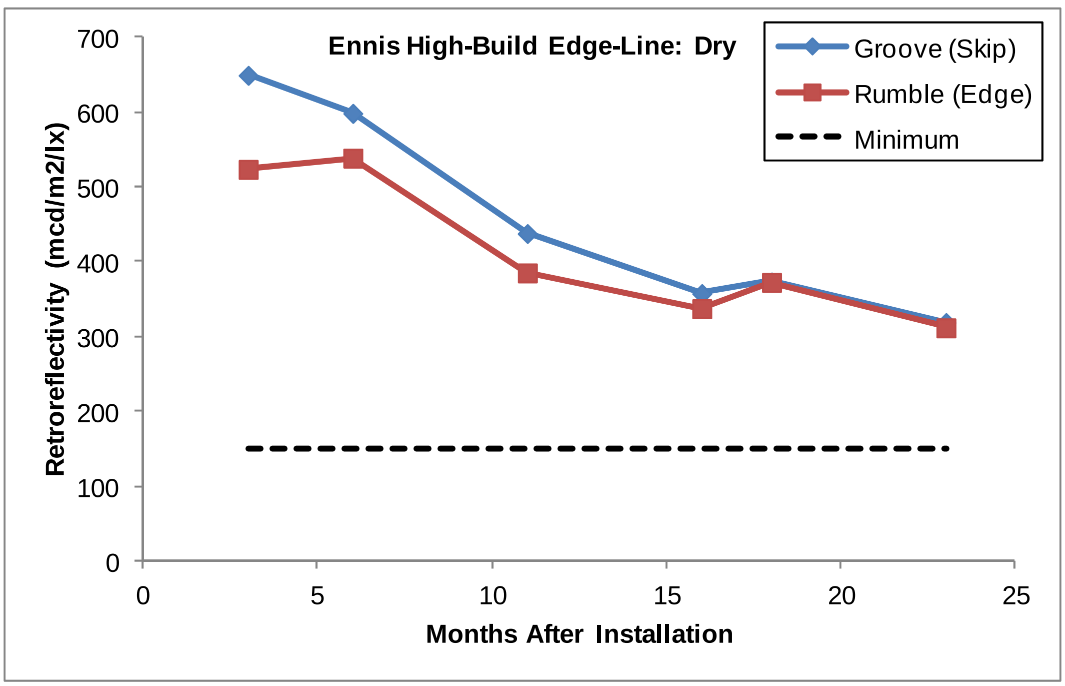

Figure 32. An example of a time plot for dry conditions.

Table 10. Estimated marking lifetime based on maintaining minimum retroreflectivity for dry and three wet conditions.

Marking	Placement	Type	Number of months that retroreflectivity was above the minimum 150 cd/m²/lx*			
			Dry	Recovery	1 in/hr	2 in/hr
3M High-Build	Groove	Edge		16.5	11	8.25
		Skip		8	6	3
	Rumble	Edge		12	11	9.5
	Surface	Edge		7.5	4	3
		Skip	NA	8	7.25	3
3M Tape	Groove	Edge			**21**	**16**
		Skip		4.5	14	4
	Surface	Edge		9.5	9	8.75
		Skip	15.25	9	8	7.75
3M Thermo	Groove	Edge		12	3	3
		Skip		16	3	3
	Surface	Edge		9	6.5	3
		Skip	NA	9.75	6	3
Ennis High-Build	Groove	Skip		3	3	3
	Rumble	Edge		16.5	3	3
Ennis MMA	Groove	Edge		6.75	6.5	3
		Skip		6	7	4
	Surface	Edge		3	3	3
		Skip	NA	5.5	3	3
Epoplex	Groove	Edge		3	3	3
		Skip		3	3	3
	Surface	Edge		3	3	3
		Skip	NA	3	3	3

*Blank cells indicate markings which did not fall below the minimum in the 23-month test period. Cells marked "NA" had insufficient data to make an estimate. These values were influenced by harsh winter conditions, and are likely not typical.

Summary

Over the 23-month period covered by these tests, the 3M Tape was the only marking to have a mean retroreflectivity above the recommended minimum during wet conditions. The 3M High-build had a mean close to the minimum recommended value, while the rest of the markings fell well below.

For each marking, the grooved line had significantly higher retroreflectivity than its surface-applied counterpart. For the only marking which utilized all three Placements (3M High-build), no significant difference was found between the grooved and rumble-striped lines.

The damage sustained during the first winter had the most impact on retroreflectivity. Reductions in retroreflectivity after the second winter were much less severe. The mean retroreflectivity for each marking dropped below the minimum after the first winter. The 3M Tape and the Ennis High-build had the highest mean retroreflectivity after the first winter and the second winter.

Grooved and rumble-striped markings were affected similarly by the first winter, and had significantly higher means than the surface-applied markings. The rumble-striped markings were not significantly affected by the second winter, and had significantly higher retroreflectivity than both grooved and surface-applied markings.

The grooved 3M Tape was the only marking to have a mean above the minimum after the first winter, and the only marking to have a mean close to the minimum after two winters. All surface-applied markings had extremely low retroreflectivity (between 11 and 54 $mcd/m^2/lx$) after the first winter, and the second winter (between 8 and 32 $mcd/m^2/lx$).

For most markings, edge-lines had significantly higher retroreflectivity than skip lines, likely due to the increased wear and tear experienced by skip lines. The 3M Thermoplastic and Ennis MMA were exceptions, however, as no difference was found between edge and skip lines for these markings. This suggests that these markings are more resilient to wear caused by normal traffic.

DISCUSSION

In the previous Wet Visibility Phase III project, a table was developed to show the required retroreflectivity for a 2- or 3-second visibility distance. These data are shown in Table 11.

Table 11. Required Retroreflectivity by Speed for Dry and Wet Night Conditions.

	2 Second		3 Second	
Speed	**Dry**	**Wet**	**Dry**	**Wet**
10	2	3	4	7
15	4	7	8	17
20	6	12	15	42
25	10	23	30	108
30	15	42	58	275
35	24	79	115	702
40	37	147	226	1789
45	58	275	446	4563
50	92	514	879	11638
55	144	959	1731	29679
60	226	1789	3409	75690
65	356	3340	6714	193031
70	559	6235	13223	492282
75	879	11638	26045	1255453

Using the table above and the mean edge-line retroreflectivity for 1 in/hr rain conditions, the maximum speed for each marking was determined for the pre-winter and post-winter average retroreflectivity for 2- and 3-second visibility distances. Table 12 shows the speeds for the overall average retroreflectivity of each marking (bolded rows), followed by the speeds for each type of Placement.

Table 12. Maximum Speed (mph) for 2- and 3-Second Visibility by Marking and Placement.

	2 Seconds			3 Seconds		
	0 Winters	1 Winter	2 Winters	0 Winters	1 Winter	2 Winters
3M HB	**40**	**35**	**30**	**25**	**20**	**20**
Groove	45	35	35	30	25	20
Rumble	45	35	35	30	25	25
Surface	35	20	15	25	10	10
3M Tape	**45**	**35**	**35**	**30**	**25**	**20**
Groove	45	40	35	30	25	25
Surface	45	30	25	30	20	15
3M Thermo	**40**	**30**	**30**	**25**	**20**	**20**
Groove	35	35	35	25	25	20
Surface	40	25	25	25	15	15
Ennis HB	**35**	**35**	**35**	**25**	**20**	**20**
Rumble	35	35	35	25	20	20
Ennis MMA	**40**	**30**	**30**	**25**	**20**	**20**
Groove	40	30	30	25	20	20
Surface	35	25	25	25	15	15
Epoplex	**35**	**25**	**25**	**25**	**15**	**15**
Groove	35	30	30	25	20	20
Surface	35	15	15	20	10	10

In order to easily assess how each marking performs in different aspects, a ranking system was used. The performance of each marking across Placement types was ranked for Detection Distance, Skip Count, Best Marking, Overall Best Marking, wet retroreflectivity, durability, Presence, and estimated edge-line lifetime. The mean retroreflectivity for 1 in/hr rain conditions was used for the wet retroreflectivity rank, and the percentage of retained retroreflectivity after the second winter was used for the durability rank. For each category, a rank of 1 is considered the best. Where possible, Student-Newman-Keuls (SNK) groupings were used to determine the rank (Table 13). If two or more markings performed similarly, and therefore had the same SNK grouping, they received the same rank. The categories which used the SNK groupings include Detection Distance, Skip Count, wet retroreflectivity, and durability. All other categories were ranked based on mean values. Table 14 shows the ranking table with the top two performers in each category highlighted.

Table 13. Example of rank based on SNK grouping.

SNK Grouping	Rank
A	1
AB	2
B	3
BC	4
C	5

Table 14. Marking rank for different aspects of performance.

Marking	Placement	Detection Distance Rank	Skip Count Rank	Best Marking Rank	Overall Best Marking Rank	Wet Retro-reflectivity Rank	Durability Rank	Mean Presence Rank	Edge-Line Lifetime Rank
3M HB	Groove	1	6	8	6	2	2	4	2
	Rumble	1	2*	3	2	2	2	11	2
	Surface	1	5	7	6	5	4	5	5
3M Tape	Groove	1	5	2	6	1	2	1	1
	Surface	1	2	5	3	2	4	6	3
3M Thermo	Groove	1	5	8	6	3	1	8	6
	Surface	4	1	8	6	4	3	7	4
Ennis HB	Rumble	1	4*	4	4	3	1	12	6
Ennis MMA	Groove	1	7	6	5	3	2	9	4
	Surface	3	3	7	5	5	3	10	6
Epoplex	Groove	2	7	7	6	4	2	2	6
	Surface	1	6	1	1	6	4	3	6

*Skip lines for these sections were grooved.

LIMITATIONS OF THE STUDY

Limitations of this study include the missing data for skip lines beyond the 11th month, and the fact that not all markings utilized all three Placements. Only the 3M High-build had grooved, rumble-striped, and surface-applied sections, and only two markings total utilized the rumble strips. This makes it difficult to make concrete conclusions about the effect of rumble-strips. Estimated lifetime was determined using a line created by six points of data over 23 months. A more accurate estimate may have been made if retroreflectivity was measured more frequently, such as once per month. In addition, the severe winter weather experienced in Blacksburg during the first winter exposed the markings to uncommonly high amounts of snow-plowing and chemical treatments, which likely had a strong negative effect on the marking lifetime. As such, the estimated lifetimes of the markings in this report are likely much lower than typical. Presence was calculated using available images of the pavement markings taken during the 23rd month. The accuracy of the analysis would likely be enhanced by using a method which analyzed the entire length of the marking, or a similarly large section for each marking that was representative of the entire marking.

COSTS AND BENEFITS ASSESSMENT

It is important to note that the cost-benefit analysis presented here is based purely on the premise of maintaining a minimum retroreflectivity of 150 mcd/m^2/lx under wet conditions. The analyses were performed based on the 1 in/hr rain conditions. An analysis based on dry retroreflectivity was not possible because no estimates of marking life were able to be made with the existing data. The cost-benefit analysis for the performance of these products was conducted in two ways. The first was an analysis based on the predicted lifetime from the durability analysis, and the second considered the visibility distance. The installed material costs (Table 15) were based on estimates provided by the material manufacturers (Note that the blank cells represents conditions that were not tested). The costs for the grooving were based on national averages. However, as the rumble strips are routinely installed on select highways, the cost of the rumble strips was dealt with both as an additional cost and as no cost.

Table 15. Estimated cost per linear foot of installed materials.

	Cost per foot installed (Dollars)		
	Surface	**Groove**	**Rumble**
3M High-Build	$0.30	$0.65	$4.30
3M Tape	$2.80	$3.50	
3M Thermo	$0.55	$1.08	
Ennis High-Build	$0.165		$4.165
Ennis MMA	$1.78	$2.48	
Epoplex Polyurea	$0.94	$1.64	

It is important to note the limitations of this cost assessment. This is a simplified theoretical cost assessment and assumes the following:

- The markings will be replaced whenever the retroreflectivity drops below the minimum retroreflectivity of 150 mcd/m^2/lx under wet conditions.
- The material is replaced with the same material. This would include the grooving and the possibly of the rumble strip. Note that in practice there are other options such as tape can be painted over and the MMA material can be recoated with a thinner layer of the same material.

A full cost benefit analysis can be undertaken by the VDOT which is linked to standard VDOT procedures and possible supplier warranties. The analysis also does not consider eradication of the existing markings at a cost of approximately $2.50 per foot.(Eradication was not considered as many products are not eradicated but rather recoated with similar materials to refresh performance).

For the lifetime cost consideration, the estimates were based on the results shown in Table 10 for 1 inch per hour of rain. Using these values, the number of line replacements per year was calculated by dividing the estimated lifetime by 12 months. This was then multiplied by the cost per linear foot of the installed material. These results are shown in Figures 33 and 34. Figure 34 excludes the cost of rumble strip installation. It is important to note that the lifetimes were estimated based on the 150 mcd/m^2/lx limit, and that it also assumes that the markings would be replaced more than once a year (which is not likely). As shown by these figures, when the cost of the rumble striping is excluded, the rumble-striped markings become the most cost-effective.

Another analysis was performed using the detection distance as measured in the visibility experiment after markings were in place 5-6 months. The cost per linear foot installed for each of the materials was divided by the visibility distance to create a cost per foot of visibility distance. It is important to note that this is a metric which is based on the material type only, which means that adding additional material and additional cost may not necessarily increase the visibility distance. The results are shown in Figure 35 (including the cost of rumble-striping) and Figure 36 (excluding the cost of rumble-striping). Again, when the cost of rumble-striping is excluded, the rumble-striped markings become the most cost-effective.

Figure 37 shows the cost based on estimated lifetime by the cost per foot of visibility distance. All four installations of the high-build paints are shown to be the most cost-effective when both values are considered.

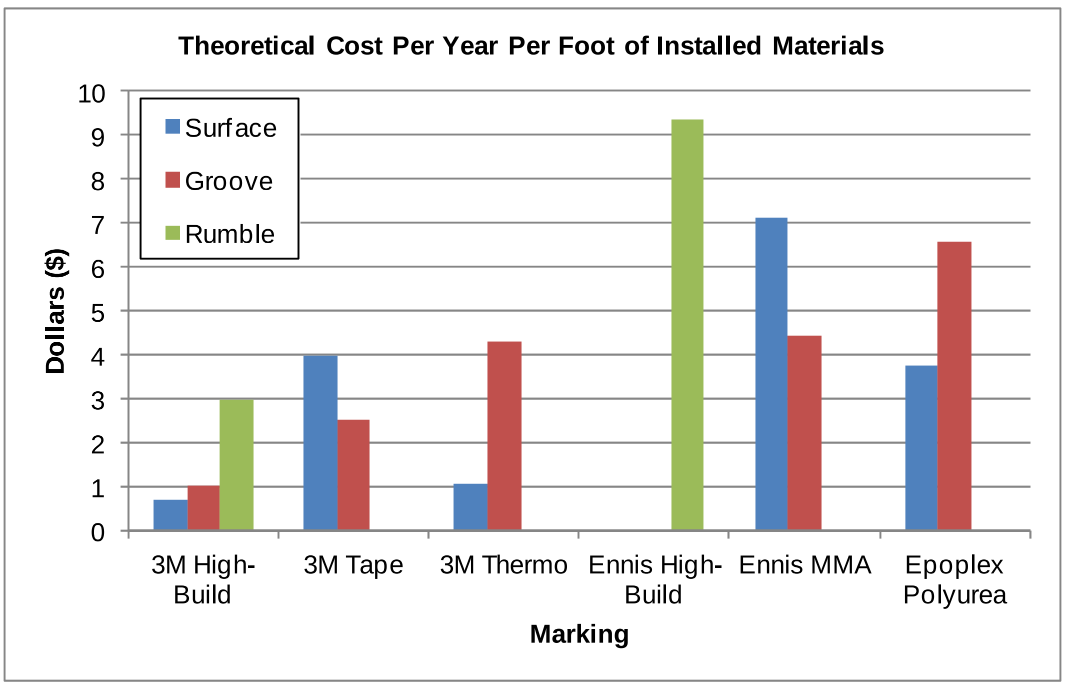

Figure 33. Cost based on estimated lifetime for maintaining wet retroreflectivity for 1 in/hr of rain.

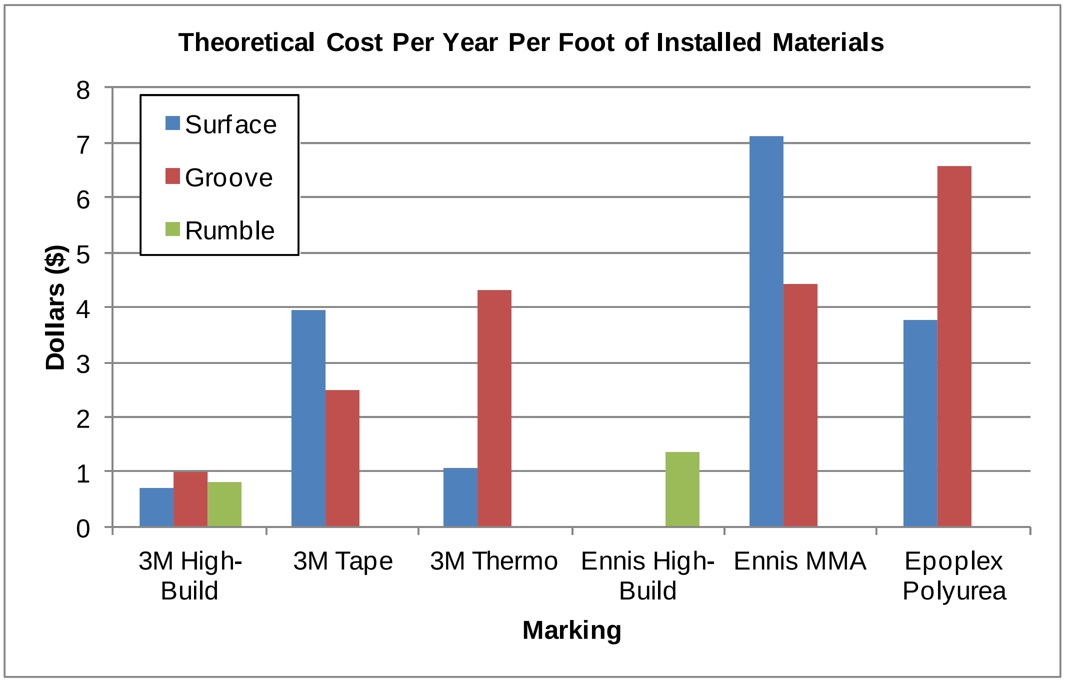

Figure 34. Cost based on estimated lifetime for maintaining wet retroreflectivity for 1 in/hr of rain with rumble-striping excluded.

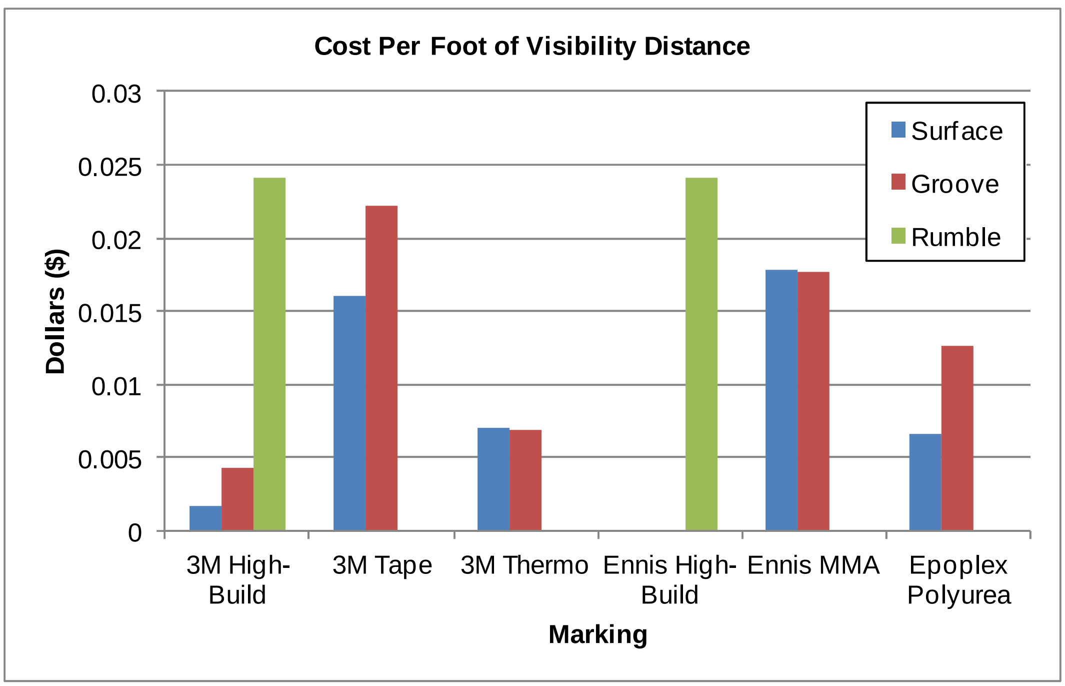

Figure 35. Cost per foot of visibility distance.

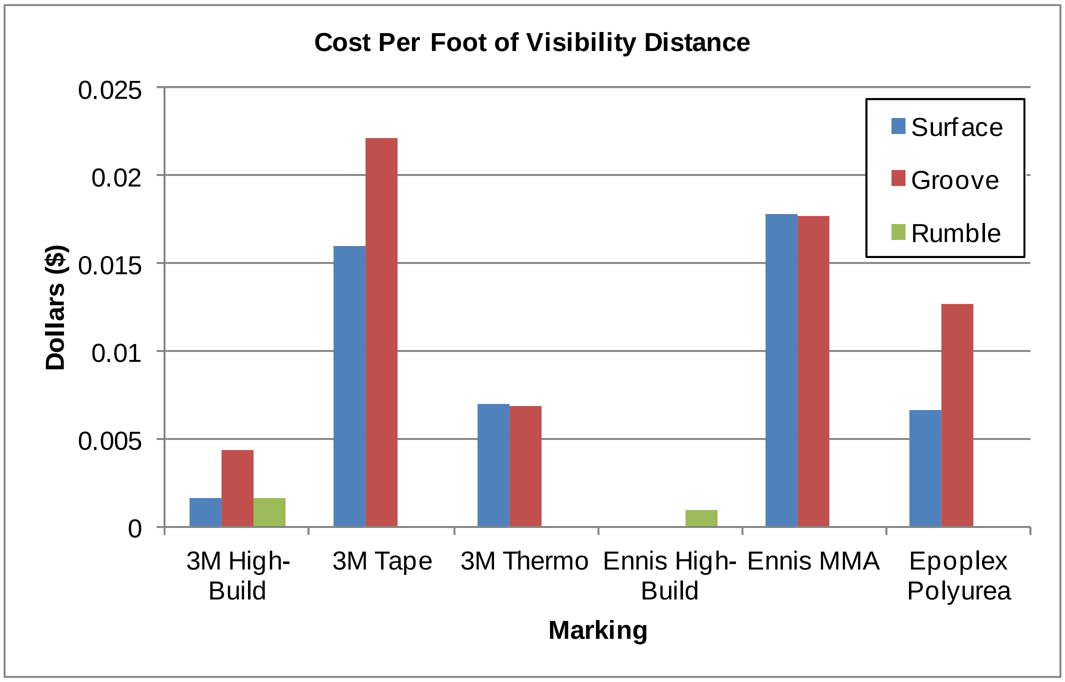

Figure 36. Cost per foot of visibility distance with rumble-striping excluded.

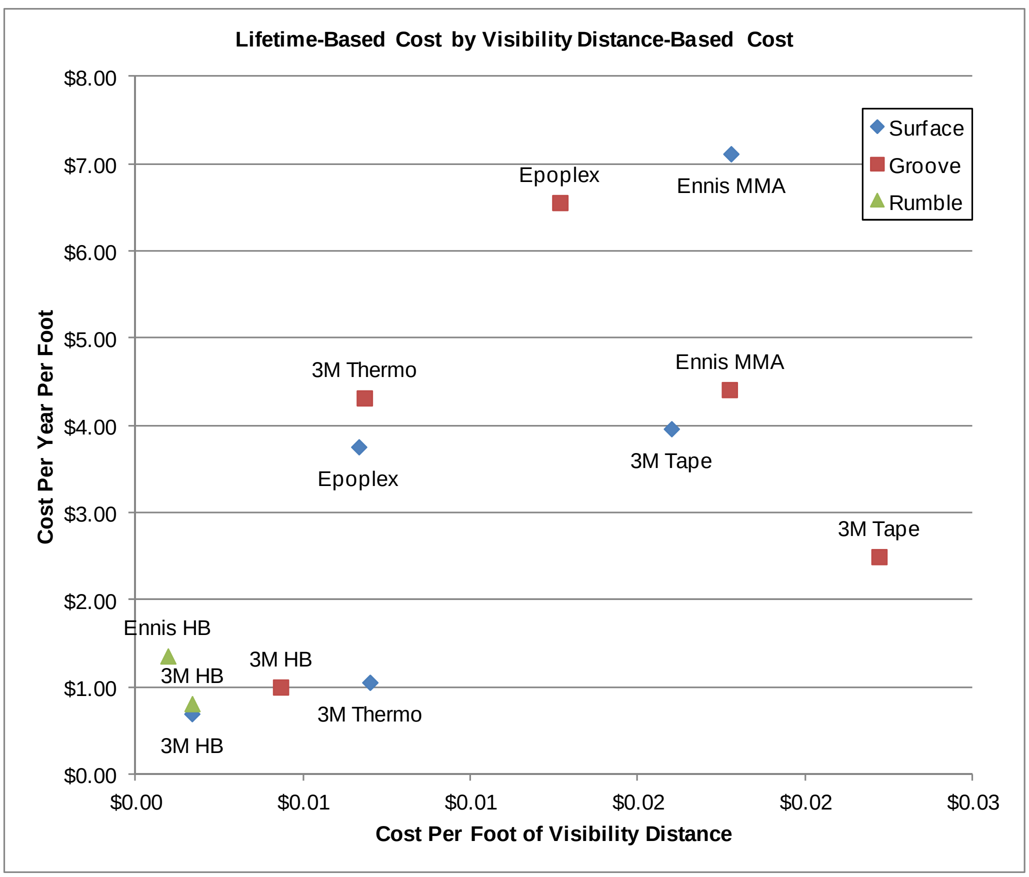

Figure 37. Cost for each marking by both estimated lifetime and cost per foot of visibility distance.

This cost-benefit analysis shows that the low cost of the high-build paints, which had similar or better performance than more expensive markings for the visibility study, offset the increased cost associated with the short estimated lifetime, making the high-build paints the most cost-effective markings.

CONCLUSIONS

- *How are the visibility needs of drivers related to retroreflectivity?* Detection Distance was shown to increase along with calculated retroreflectivity, but began to show diminishing returns above 150 mcd/m^2/lx. Note that this value is lower than the value specified in the previous wet visibility efforts. This is likely due to the application of the testing in a real world environment versus the testing that was performed in a controlled environment.

- *How does retroreflectivity vary among different types of markings?*

  — The 3M Tape had the highest mean retroreflectivity, and was the only marking to have a mean retroreflectivity above the minimum.

  — The high-build paints were among the top performers, while the polyurea was the lowest performer.

- *What impact does Placement have on retroreflectivity?* Placing markings in grooves or rumble strips significantly improves retroreflectivity performance over the life of the marking as compared to the same marking placed on the surface of the roadway.

- *How does retroreflectivity of a marking change over time?* The mean retroreflectivity of all tested markings, except the grooved 3M Tape, fell below the minimum after the first winter, and all markings fell below the minimum after two winters.

- *How does retroreflectivity of edge and skip lines differ?* Skip line retroreflectivity was significantly lower than edge-lines for all markings except the 3M Thermoplastic and Ennis MMA.

- *What impact does winter plowing have on retroreflectivity?* Retroreflectivity was significantly reduced after each winter; however, the first winter resulted in the most severe losses.

- *What is the lifetime of each marking with respect to a 150 mcd/m2/lx minimum?*

  — For 1 in/hr rain conditions, only two markings had a lifetime of more than 1 year.

  — For 2 in/hr rain conditions, only one marking had a lifetime of more than 10 months.

  — A large number of markings had fallen below the minimum before 3 months.

- *How do these factors interact?*

  — Markings installed in grooves retained at least twice as much retroreflectivity after the first winter when compared to their surface-applied counterparts, and for the 3M High-build, the grooved markings retained significantly more retroreflectivity than the rumble-striped markings.

  — The grooved 3M Thermoplastic retained the most retroreflectivity after the first winter out of all the markings with 94% retained.

  — After two winters, the rumble-striped markings had significantly higher rates of retention than the grooved markings.

  — For surface-applied markings, the 3M Thermoplastic and Ennis MMA had the highest rates of retention.

  — The grooved 3M Tape edge-line had the longest estimated lifetime for all wet conditions.

  — The Epoplex polyurea and the grooved 3M Tape had the highest Presence after 23 months, each with 90% or more of the marking still intact. This measure does not consider the amount of reflective elements, however.

RECOMMENDATIONS

1. *To extend the life of pavement markings, VDOT's Traffic Engineering Division should install pavement markings in grooves or in rumble strips.* It is expected that due to cost concerns, VDOT will determine where the use of grooves or rumble strips is appropriate. It is the belief of the research team that high-speed roadways such as interstate highways and major arterials, where pavement marking visibility is more critical, should be the highest priority. Grooved markings may also be desired for high-volume roadways where markings may be exposed to higher levels of wear from traffic. In addition, some markings, such as tape, may not be a good match for rumble strips as the "crowns" of the strips would still be susceptible to plow damage, which could potentially result in portions of the marking being removed from the roadway. Marking selection is also of great importance for ensuring lasting benefit of the pavement markings. Based on the results of this study, the tape or either high-build paint would be recommended, as they had the highest performance in wet conditions, and also tended to maintain relatively high retroreflectivity over time compared to the other markings tested. While the Ennis high-build paint was only tested in a rumble strip, it is expected that a grooved version of the line would perform similarly based on the comparison between the grooved and rumble-striped 3M high-build paint.

2. *The study team should monitor the study markings on Route 460 in Blacksburg for two more years.* The team should make the measurements after each winter through 2013 and report the findings to VDOT in a brief report.

3. *Staff of VDOT's Traffic Engineering Division and the Virginia Center for Transportation Innovation and Research should perform additional cost-benefit analyses to address standard VDOT policy, procedures, and practices and possible supplier warranties.*

BENEFITS AND IMPLEMENTATION PROSPECTS

Implementation of the study recommendations should provide the following benefits:

- greater visibility of pavement markings for drivers in wet night conditions
- improved visibility of roadways through the improvement of lane and roadway delineation
- improved safety through increased wet night visibility conditions by a reduction in lane departure and run-off-road crashes.

However, the following may also occur:

- possible decrease in the life of a marking in order to maintain the minimum specification
- possible increase in the rate of reinstallation in order to maintain the minimum specification.

The implementation prospects are high. VDOT's Traffic Engineering Division is preparing a pavement marking policy. It is anticipated that the recommendations and results of this study will be incorporated in this policy.

ACKNOWLEDGMENTS

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REFERENCE

Gibbons, R.B., and Williams, B.M. *The Refinement of Drivers' Visibility Needs During Wet Night Conditions: Wet Visibility Project Phase III.* VCTIR 11-R20. Virginia Center for Transportation Innovation and Research, Charlottesville, 2011.