Highways for LIFE Technology Partnerships Program

Final Report Phase I

Temporary Wet-Weather Pavement Markings for Work Zones

Project Summary

This project aims to refine and evaluate a paint and drop-on element-based all-weather pavement marking system customized for work-zone applications. The pavement marking system under development offers unique value in providing superior guidance to the driver under dry and wet weather conditions. The shorter durability requirements in work zones enable a low-cost alternative to existing higher-cost, more durable products. We expect this special all-weather work zone pavement marking system to promote work zone safety in especially attention-demanding work zones.

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SUMMARY OF THE WORK COMPLETED

This final report summarizes the work completed during Phase I of the project. The details of the work performed and associated findings are given in Appendices A-1, A-2, A-3, and B of this report.

SUMMARY OF OVERALL TASK PROGRESS

Table 1. Revised Gantt chart showing the overall project schedule.

WBS	Tasks	Start	End	Duration (Days)	% Complete	Days Complete	Days Remaining	Nov-07	Dec-07	Jan-08	Feb-08	Mar-08	Apr-08	May-08	Jun-08	Jul-08	Aug-08	Sep-08	Oct-08	Nov-08	Dec-08	Jan-09	Feb-09	Mar-09	Apr-09	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09
1	Phase I	11/01/07	7/31/08	273	100%	273	0																								
1.1	Task 1	11/01/07	1/2/2008	62	100%	62	0																								
1.2	Task 2	1/03/08	5/31/2008	149	100%	149	0																								
1.3	Task 3	6/01/08	6/30/2008	29	100%	29	0																								
1.4	Phase I Review by AOTR	7/01/08	7/31/08	30	0%	0	30																								
2	Phase II	8/01/08	10/31/09	456	0%	0	456																								
2.1	Task 4	8/1/2008	1/31/2009	183	0%	0	183																								
2.2	Task 5	12/1/2008	7/31/2009	242	0%	0	242																								
2.3	Task 6	8/1/2009	10/31/2009	39	0%	0	39																								
	QPR								×			×			×			×			×			×			×			×	

PHASE I

Task 1: Initial pre-screening of candidate pavement marking systems

This task was completed. A total of 24 pavement marking samples were installed on a New Orleans, LA test deck in November 2007. A time-series of their retained retroreflective properties collected through January 2008. Three prototype all-weathering markings were identified to carry into Task 2. The details of the work performed in the New Orleans test deck are given in Quarterly Progress Report: November 2007 – January 2008 and Quarterly Progress Report: February 2007 – April 2008.

The details of this task are given in Appendix A-1 and Appendix A-2.

Task 2: Install markings at TTI rain range and the human factors evaluation

This task was completed. Work on the human factors study begain in February 2008. An experimental plan was developed for a dynamic field study of the visibility properties of the three prototype all-weathering markings chosen based on the Task 1 results. The experimental plan was carried out in collaboration with Texas Transportation Institute and a final report issued in the form of a technical paper submitted to the Transportation Research Board 2009 Annual Meeting. The details of the work performed in the human factors study are given in Quarterly Progress Report: February 2007 – April 2008 and Quarterly Progress Report: May 2008- July 2008.

The results of the study found that all three all-weather marking prototypes had statistically the same detection distances in both continuous rain and wet road conditions, which were statistically longer than the conventional glass bead-on-paint markings commonly used in work zones. Based on these results in combination with the results of Task 1 the all-weathering marking construction proposed to be carried forward into the Phase II is:

> 3M medium size high refractive index dual-optics drop-on elements at a drop rate of 8g/lineal ft in combination with MODOT Type P (or AASHTO M247 Type I) drop-on 1.5 index glass beads at a drop rate of 12g/lineal ft applied in a double-drop onto a high-build waterborne paint applied at a 20 mil wet film thickness.

The development of the task plan for Task 2 is given in Appendix A-2 and the results of the field experiment are given in Appendix A-3.

Task 3: Coordination and logistical planning for field work-zone evaluation for Phase II

This task was completed. A general experimental plan for the Phase II field evaluations of the all-weather work zone pavement marking system was created to serve as the foundation for individual experimental plans required for the Phase II field studies in each candidate state. An experimental plan has been developed as given in Appendix B.

A Request for Proposal (RFP) was also written and circulated to research organizations having working relationships with the two state DOTs that have already committed to participating in Phase II, Washington State and North Carolina.

A formal proposal to conduct the all-weather paint for work zones field evaluation in North Carolina was received from the Department of Civil, Construction, and Environmental Engineering at North Carolina State University. The Department of Civil and Construction Engineering at Oregon State University has also expressed interest and is in the process of preparing their proposal for conducting the field evaluations in the state of Washington.

PHASE II

Task 4: Final Selection of Work Zones

This task has not yet started.
Duration: 4 Months, Deliverables: QPR

Task 5: Field demonstrations and evaluations

This task has not yet started.

Duration: 8 Months, Deliverables: 2 QPRs

Task 6: Technology Transfer

This task has not yet started.

Duration: 3 Months, Deliverables: Project Final Report

3M ANALYSIS OF PRODUCT MANUFACTURABILITY AND PURCHASE POTENTIAL

3M currently manufactures and sells All-Weather Paint products for use as maintenance markings in durable pavement marking applications. The temporary all-weather paint for work zones prototypes being optimized in this study will utilize manufacturing techniques similar to the current product. The equipment to apply and install the test product is already in place in many states, or can be developed very quickly with known procedures. The only difference is the application rates, which are easily adjusted via the control levers on the equipment. We see great purchase potential for this product, especially in the event of successful field demonstrations in Phase II work zone field evaluations. Phase I of the project indicated that the experimental markings provided an unequivocal improvement in visibility distances over conventional pavement markings especially under rainy conditions when driver needs better guidance. Many states already have expressed great interest in a product with a reasonable cost that can also provide nighttime visibility under rainy conditions. However, many of these states also rely on research studies that indicate a measurable benefit before they specify such application. Should the improved visibility positively impact the surrogate measures of safety in the field evaluations in Phase II, we foresee a great potential for general acceptance in the marketplace, and eventually an improvement in driver safety especially in work zones.

APPENDIX A-1: TASK 1 - INITIAL PRE-SCREENING OF CANDIDATE PAVEMENT MARKING SYSTEMS

Task 1, the initial pre-screening of candidate pavement marking systems, their installation on a test deck, and retroreflectivity data collection have been completed during this first reporting period.

The primary focus of the 3M research team in this quarter was to install the prototype all-weather pavement marking systems on the test deck and evaluate their durability in terms of retention of retroreflective properties over time under real-world traffic exposure conditions. A test deck for these evaluations was arranged in New Orleans, LA with the assistance and cooperation of the Jefferson Parish Sign & Marking Department of the Department of Engineering, Traffic Engineering Division. The test deck is the right hand lane of south bound Whitney between Carol Sue Avenue and Copper Road in Jefferson Parish (Figure 1). The ADT on this road segment measured in May 2007 was 6200, the details of which are shown in Table 2.

Figure 1. Highways for Life New Orleans Test deck

Table 2. Annual Daily Traffic (ADT) for New Orleans Test Deck location

Interval Begin	Weekday Avg
12:00 AM	44
1:00 AM	15
2:00 AM	15
3:00 AM	14
4:00 AM	29
5:00 AM	86
6:00 AM	372
7:00 AM	704
8:00 AM	612
9:00 AM	351
10:00 AM	304
11:00 AM	308
12:00 PM	370
1:00 PM	385
2:00 PM	356
3:00 PM	407
4:00 PM	389
5:00 PM	384
6:00 PM	309
7:00 PM	258
8:00 PM	195
9:00 PM	134
10:00 PM	117
11:00 PM	73
Total	6233

Twenty-two (22) experimental all-weather work zone pavement marking samples were installed on the test deck on November 28, 2007. Figure 2 through Figure 6 illustrates the test deck installation and measurement efforts. The composition of each prototype was carefully customized to generate a rich dataset from a wide range of candidate pavement marking samples. Variations in all-weather prototypes included paint thickness (mil), element size (three sizes), element proportion (percentage of 2.4 index elements and 1.9 index elements in the element mixture) and drop rate (gram/foot). In the samples, two types of elements (surrounded by either 2.4 or 1.9 index beads) were tested in addition to other types of common glass beads. A single type of high-build traffic paint was used for all the prototypes. In addition to the prototypes two commercially available pavement marking tapes were also installed on the test deck to serve as controls.

The markings were applied in a longitudinal CEN-style test deck configuration with a hand cart. Four inch by three foot (4” x 3’) lines were installed at the centerline, left wheel track, right wheel track, and right edge line positions. We prefer this longitudinal configuration as opposed to transverse configuration (which is the common practice in many test decks), because these markings will eventually be installed in the longitudinal configuration, which is also the direction of traffic. This way, the tire hits are in the same direction as the retroreflectivity measurements, which is also congruent with the driver view. The test lines were sprayed through a mask and the drop-on elements, and a subsequent drop of glass beads were applied by hand using shakers. This is common industry practice for the installation of such multiple construction research test decks. Standard Retroreflectance (R_L, cd/m^2/lx) measurements were made using LTL-X handheld pavement marking retroreflectometers on November 29, the day after installation. The 3M team made follow-up measurements on December 10-11, December 17-18 with the final follow-up January 8-9. These represent measurements at effectively 0, 11, 18 and 41 days after installation. Table 3 shows the final set of selected and installed pavement markings on the test deck.

Table 3. Prototype All-weather Work Zone Pavement Markings installed on the New Orleans Test Deck

Prototype Number	Wet Paint Film (mils)	Element Size	Drop Rate (g/lineal ft)	2nd Drop beads	Drop rate (g/lineal ft)
1	15	Small	4	M247 Type 1	12
2	15	Small	8	M247 Type 1	12
3	15	Small	12	M247 Type 1	12
4	20	Small	4	M247 Type 1	12
5	20	Medium	4	M247 Type 1	12
6	20	Medium	8	M247 Type 1	12
7	20	Medium	12	M247 Type 1	12
8	15	Medium	4	M247 Type 1	12
9	20	Medium*	4	M247 Type 1	12
10	20	Medium**	4	M247 Type 1	12
11	20	Medium***	4	M247 Type 1	12
12	20	Medium	4	MO Type P	12
13	20	Medium	4	M247Type 3	12
14	20	Medium	4	1.9 index Type 1$^{@}$	12
15	25	Large	4	M247 Type 1	12
16	25	Large	8	M247 Type 1	12
17	25	Large	12	M247 Type 1	12
18	20	Large	4	M247 Type 1	12
19	15	--	--	M247 Type 1	12
20	20	--	--	M247 Type 3	12
21	15	--	--	1.9 index Type 1$^{@}$	12
22	25	Large	4	MO Type P	12
Controls					

23	3M™ Stamark™ Wet Reflective Removable Tape Series 780
24	3M™ Stamark™ Extended Season Tape Series 380

* = Only 2.4 index elements; ** = 50:50 blend of 2.4 index and 1.9 index elements; *** =only 1.9 index elements;[@] =1.9 index beads with the size distribution similar of M247 Type 1

Figure 2. CEN-style test deck configuration on the New Orleans Highways for Life Test Deck.

Figure 3. Illustration of test line installation procedure at Right Wheel track location.

Figure 4. Illustration of paint line application showing masks used for 4" x 3' test lines

Figure 5. View of completed New Orleans test deck installation

The research team conducted initial and subsequent follow-up R_L measurements on all of the test markings – prototypes and controls. The focus of the measurements was on the right wheel track location and the right edge line location. Our earlier similar installations indicate that these two locations represent the locations with the greatest and fewest number of wheel hits, respectively. R_L was measured under dry, wet recovery and simulated rain conditions. Measurements were made following the procedures outlined in ASTM E1710 (dry), E2177 (wet-recovery), and E2176 (continuous wetting), as well as using a rain simulator designed to meet the requirements of EN1436. A view of our rain simulator is shown in Figure 6. Data collection efforts were in part designed to assess the measurement variability of different R_L test methods, especially measurement of R_L under continuous wetting method.

The data collection is completed. The analysis of the data had been conducted in the next reporting period.

Figure 6.   EN 1436 rain simulator

PLANNED WORK FOR THE NEXT QUARTER

Within the next quarter, we have planned for the following tasks:

Retroreflectivity Data Analysis and Material Selection for the Field Experiment at TTI

The retroreflectivity data obtained in the New Orleans test deck were analyzed in the succeeding quarter. We expect this analysis to provide us with insight on the durability characteristics of each pavement marking test sample. This data contained standard 30-meter retroreflectance [mcd/m^2/lx] of each tested sample under dry and wet conditions (using a modified version of the standard continuous-wetting method with a more reasonable rain rate). The tests were conducted at different levels of traffic exposure, providing an outline for the degradation curve as a function of vehicle passes over the markings.

A comparison between sample markings at different exposure levels was performed and we expected some of the test markings to be found not suitable for further testing. We have chosen three test markings to be carried forward onto the field experiment.

Kick-off meeting with state agency representatives and TTI research team

The final execution of the subcontract was immediately followed by a teleconference between 3M and TTI research team members. In addition, we had a face-to-face meeting with TTI team in New Orleans at an American Traffic Safety Systems Association (ATSSA) meeting. The ATSSA venue was timely and convenient to have the initial meeting not only with the TTI team, but also with state agency representatives. Two of the candidate states, Washington and North Carolina showed interest in participating in the project in Phase II, and will have representatives attending to the ATSSA meeting in New Orleans. This way, the trips to each state for separate kick-off meetings was combined. It is our understanding that some of the future work zones are already planned more than a year in advance, requiring us to get involved in the process early on.

Meeting with TTI research team at College Station for the development of the detailed experimental plan

3M team members visited TTI facilities and team members to develop the detailed experimental plan for Task 2. Part of the plan development required a set of test markings be installed in the rain range at TTI to assess feasibility of the conceived plan. It was our intent to evaluate a wide battery of test materials, yet we were limited in the available length of the rain range. An initial installation of viable test samples and a feasibility assessment from a visibility perspective was required for developing a sound and viable experimental plan.

For that purpose, we foresaw a nighttime pilot experiment to determine the installation location of each test sample in the rain range to determine the maximum number of test samples that we can comfortably accommodate in the rain range, and the installation locations for the test samples for dry condition evaluation. This feasibility assessment took place during the week of February 18, 2008.

PROBLEMS ENCOUNTERED

We have experienced delays in the contract execution for the project, which delayed the initiation of the project by nearly two months from the original plan. As a consequence, we could not perform the Task 1 test sample evaluations in Minnesota as originally planned due to typical early Minnesota snowfall. Instead, we decided to carry out the evaluation in a New Orleans test deck. Moving the operations to New Orleans required unplanned travel for personnel and shipping of equipment. However, relocating the work to New Orleans allowed us to maintain our overall 24 month timeline.

We initiated the subcontract process with TTI upon the execution of the primary contract with FHWA. Yet, the subcontract process also took longer than we expected. The contract with TTI did not get finalized until January 18. The discussions of Tasks and development of the detailed task plan could start only after the execution of the subcontract. As a result, the Task 2 test plan was delayed until February 29, 2008.

Overall, at this point, we had measurable progress toward project goals as planned, albeit with a nearly two-month shift in the overall project timeline.

APPENDIX A-2: TASK 1 AND TASK 2: SELECTION AND INSTALLATION OF THREE CANDIDATE PAVEMENT MARKINGS SYSTEMS AT TTI

In summary, we have identified three candidate experimental pavement markings, installed them in the TTI Riverside facility alongside two other pavement markings as control conditions, collected retroreflectivity data on these markings, and conducted a pilot human factors experiment to finalize the experimental design for the Task 2 human factors experiment.

Retroreflectivity Data Analysis and Material Selection for the Field Experiment at TTI

Phase I – Task 1: Initial pre-screening of candidate pavement marking systems

The objective of this task was to pre-screen twenty-two (22) alternative prototypes constructions to identify the three (3) best performing all-weather work zone pavement marking systems with promising retroreflectivity characteristics under dry and wet weather conditions for further evaluation in Task 2. The prototype constructions and controls installed on the New Orleans test deck are listed in Table 4. The test markings were installed on November 28, 2008 and the ensuing initial measurements were conducted the next day. The 3M team made subsequent measurements on December 10-11, December 17-18 with the final measurement on January 8-9. These measurements were conducted effectively 1, 11, 18 and 41 days after installation. The purpose of these measurements was to determine the durability of retroreflectivity of each prototype in a customized field test.

The test and control markings were applied in a longitudinal CEN-style test deck configuration at four locations across the road: centerline, left wheel track, right wheel track, and right edge line. The criterion for evaluating the experimental prototype in Task 1 was the durability and more specifically retention of retroreflectivity under dry, wet and rainy conditions. In order to effectively provide clear nighttime delineation within a work zone over time it is necessary for the markings to maintain a relatively high level of retroreflective efficiency under all weather conditions. It is well established that pavement marking retroreflectivity deteriorates at different rates depending on their position on the road. The four locations used in the CEN-style test deck configuration represent both common in-use wear (i.e., centerline and edge line) as well as "accelerated" wear conditions (i.e., left and right wheel track). The wheel track positions are subjected to greater wear (i.e., significantly higher number of wheel hits) than the edge line or centerline positions thereby providing a rapid test of the durability of the test markings. Given the duration of testing, we concentrated our attention on the accelerated wear at the right wheel track location for all of the experimental prototypes.

Coefficient of retroreflected luminance (R_L) was measured on the test pavement markings using a LTL-X portable retroreflectometer. Measurements were made using several test procedures simulating different conditions – dry, wet and rain. For the 'rain' and 'wet' conditions, the majority of measurements were made using a portable rain simulator designed by 3M Germany that fulfills the requirements of EN1436. This EN standard calls for "…artificial rainfall, without mist or fog, at an average intensity of (20 ± 2) mm/h…[0.8± 0.08 in./hr]." We were unable to make measurements of R_L 'wet' or 'rain' for test markings 1-5 in the right wheel track position on the 41st day due to a natural rain event.

Table 4. Experimental Pavement Markings installed on the New Orleans Test Deck

Prototype Number	Wet Paint Film (mils)	Element Size	Drop Rate (g/lineal ft)	2nd Drop beads	Drop rate (g/lineal ft)
Prototype All-weather Work Zone Pavement Markings					
1	15	Small	4	M247 Type 1	12
2	15	Small	8	M247 Type 1	12
3	15	Small	12	M247 Type 1	12
4	20	Small	4	M247 Type 1	12
5	20	Medium	4	M247 Type 1	12
6	20	Medium	8	M247 Type 1	12
7	20	Medium	12	M247 Type 1	12
8	15	Medium	4	M247 Type 1	12
9	20	Medium*	4	M247 Type 1	12
10	20	Medium**	4	M247 Type 1	12
11	20	Medium***	4	M247 Type 1	12
12	20	Medium	4	MO Type P	12
13	20	Medium	4	M247Type 3	12
14	20	Medium	4	1.9 index Type 1@	12
15	25	Large	4	M247 Type 1	12
16	25	Large	8	M247 Type 1	12
17	25	Large	12	M247 Type 1	12
18	20	Large	4	M247 Type 1	12
22	25	Large	4	MO Type P	12
Control and Reference Pavement Markings					
19	15	--	--	M247 Type 1	12
20	20	--	--	M247 Type 3	12
21	15	--	--	1.9 index Type 1@	12
23	3M™ Stamark™ Wet Reflective Removable Tape Series 780				
24	3M™ Stamark™ Extended Season Tape Series 380				

* = Only 2.4 index elements; ** = 50:50 blend of 2.4 index and 1.9 index elements; *** =only 1.9 index elements; @ =1.9 index beads with the size distribution similar of M247 Type 1

As noted above the main criteria for assessing the performance of the experimental prototype markings is their durability in terms of maintained level of retroreflection. Higher retained retroreflection translates to higher retained luminance and better visibility for the nighttime driver especially under rainy conditions. Since visibility is typically worst under active rainfall at night, retroreflective efficiency in ‘rain’ conditions has been chosen as the primary consideration for ranking the performance of the various prototypes. Dry retroreflective properties are also considered, but within the scope of this project we considered them a secondary consideration as long their values were greater than 200 mcd/m^2/lx, which is considered sufficient for good night visibility. Table 5 shows the 41 day results for the prototypes sorted by their $R_{L\text{-}Rain}$ values in 0.8 inch/hr simulated rain obtained using the EN 1436 rain simulator. We used this data as the basis for selection of three prototypes to take on to Task 2.

Table 5. Retroreflective efficiency at 41 days (1/9/2008) sorted by RL-Rain values in 0.8 in/hr simulated rain obtained using the EN 1436 rain simulator

Prototype Number	Wet Paint Film (mils)	Element size	Element Drop Rate	Dry	EN1436 rain simulator @0.8 in/hr	Recovery @ +45 sec
Experimental Prototype Markings						
7	20	Medium	12	517	175	283
16	25	Large	8	522	174	264
6	20	Medium	8	405	127	189
17	25	Large	12	574	124	194
14	20	Medium	4	622	105	171
12	20	Medium	4	428	103	143
13	20	Medium	4	427	98	126
9	20	Medium*	4	282	81	122
15	25	Large	4	433	67	96
22	25	Large	4	366	41	75
10	20	Medium**	4	454	36	54
8	15	Medium	4	351	34	55
18	20	Large	4	355	25	60
11	20	Medium***	4	707	18	25
5	20	Medium	4	333	*27*[a]	*59*[a]
2	15	Small	8	257	*23*[a]	*69*[a]
1	15	Small	4	265	*22*[a]	*38*[a]
4	20	Small	4	278	*22*[a]	*32*[a]
3	15	Small	12	249	*7*[a]	*22*[a]

* = Only 2.4 index elements; ** = 50:50 blend of 2.4 index and 1.9 index elements; *** =only 1.9 index elements; [a] = 18 day values for reference.

The performance of the prototypes could be broken down into four groups based on these test results. First, it is clear that element size is significant with small elements exhibiting consistently poorer durability than medium or large elements. Therefore no prototypes with small elements are considered for Task 2. Second, among those with medium and large elements higher element drop rates performed better, with 4 gram/foot drop rate performing the worst. However the benefit tapered off at higher drop rates, in that, there was no significant performance increase observed in using 12 gram/foot over the 8 gram/foot rate. Therefore, for economic considerations, no formulations using 12 gram/foot of elements are carried over to Task 2. Third group is those prototypes with 'rain' values on the order of 100 mcd/m^2/lx or greater. This leaves five (5) prototypes with relatively high performance under rain, recovery and dry conditions. Prototypes 12, 13 and 14 were found to be essentially equivalent in their rain performances. Prototype 12 employed MO Type P glass beads as the second drop optics, which gives it a cost advantage over the other two. Upon further inspection of the results, a clear durability benefit appeared in using MO Type P as the second drop optics with the medium elements. Based on our analysis, the three prototypes to carry on to Task 2 were prototypes 12, 6, and 16 as shown in Table 6.

Table 6. Final Experimental Prototype Wet-Weather Pavement Markings for Task 2

Marking	Base Prototype	Wet Film Paint[@] thickness (mils)	1st Drop Optics (drop rate/ 4 in line)	2nd Drop Optics (drop rate/ 4 in line)
EXPT A	12	20	Medium 3M dual-optics elements (4g/lineal ft)	MODOT Type P glass beads (12g/lineal ft)
EXPT B	6	20	Medium 3M dual-optics elements (8g/lineal ft)	MODOT Type P glass beads (12g/lineal ft)
EXPT C	16	25	Large 3M dual-optics elements (8g/lineal ft)	M247 Type 1 glass beads (12g/lineal ft)

[@] = High-build waterborne paint

Kick-off meeting with state agency representatives and TTI research team

The kick-off meeting was held at the ATTSA annual meeting in New Orleans in early February. The candidate state representatives and the research team members were planning to attend to this meeting in New Orleans, which was also very timely to start discussions about the involvement of these states in the project. The PI made a short presentation to the state agency representatives explaining the Highways for Life Technology Partnership Program and the objectives and tasks of this project for their support. The states were receptive and supportive, and reiterated their intent to collaborate. Further action items identified in the meeting were to determine the criteria to be sent to the states for pre-screening work zones in respective states for the spring 2009 construction season.

Installation of Experimental Pavement Marking Materials at TTI

The five test pavement marking were installed in accordance with the *Detailed Project Plan for Task 2*. The markings consisted of the three experimental prototypes chosen based on the results of Task 1 plus two reference markings (Table 7). The test markings were installed at predetermined locations at the Texas A&M University Riverside Campus. Figure 7 shows a map illustrating where each marking was installed.

Table 7. Test Pavement Markings for Task 2

Marking	Based on Task1 Prototype	Wet Film Paint@ thickness (mils)	1st Drop Optics (drop rate/ 4 in line)	2nd Drop Optics (drop rate/ 4 in line)
Experimental Marking				
EXPT A	12	20	Medium 3M dual-optics elements (4g/lineal ft)	MODOT Type P glass beads (12g/lineal ft)
EXPT B	6	20	Medium 3M dual-optics elements (8g/lineal ft)	MODOT Type P glass beads (12g/lineal ft)
EXPT C	16	25	Large 3M dual-optics elements (8g/lineal ft)	M247 Type 1 glass beads (12g/lineal ft)
Reference Markings				
Ref. 1	19	15	M247 Type 1 glass beads (12g/lineal ft)	NA
Ref. 2	23	NA	3M™ Stamark™ Wet Reflective Removable Tape Series 780	NA

@ = High-build waterborne paint

In order to allow the test pavement marking lines to be easily removed from the roadway surface after completion of the experiments, a thin black polymer film with a pressure sensitive adhesive was laminated to the road (Figure 8). The black film was laid out onto the roadway in the required configuration and tamped down to conform to the roadway surface. Four-inch wide painted lines were applied onto the black film using a self-propelled application cart with double drop capability manufactured by EZ Liner Industries (Figure 9). Target paint film application was achieved through the appropriate choice of spray tip, distance between the spray tip and road surface and application ground speed. Paint wet film thickness was calibrated prior to installation for each experimental marking. Target application of the first drop and second drop optics was achieved by calibration of delivery rates and by adjustment of distribution across the surface of the paint line (Figure 10). Calibrations for paint and optics application followed procedures used in the industry to set the application parameters on a full scale paint striping truck. For each painted line the 'stem' was painted and allowed to dry to a track free state, then the 'tails' were painted. Reference marking 2, a commercial all-weather pavement marking tape, was installed by hand and applied directly to the black polymer film, which was already on the road. This installation technique was used to insure that all markings were applied using the same protocol.

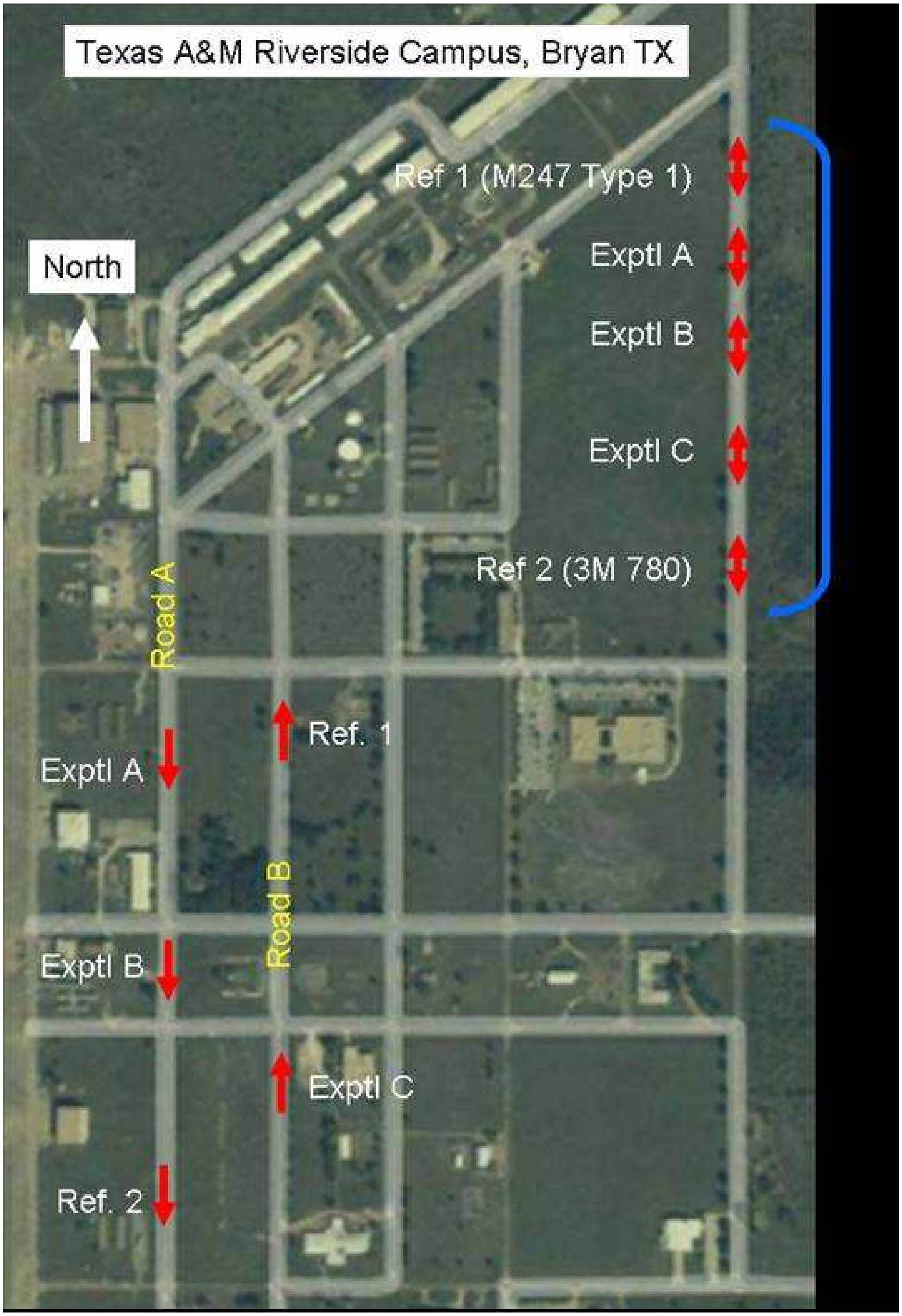

Figure 7. Map of test marking locations within the Texas A&M Riverside Campus

Figure 8. Experimental pavement marking applied to black polymer film to allow easy removal of the test markings after completion of the Task 2 experiment

Figure 9. EZ Liner walk behind application cart used to apply painted lines

Figure 10. Calibration of Element and Glass bead application rates

Standard coefficient of retroreflected luminance (R_L) measurements were conducted on the test markings at each location shortly after they were installed. Similar measurements are to be repeated periodically over the course of the experiment to account for any changes due to wear or other factors. Measurements of R_L under rain and wet conditions were also conducted on the markings installed within the rain range. Finally, a set of nighttime luminance measurements on the experimental markings in the rain range were conducted as viewed from inside the test vehicle using a CCD photometer under dry and rain conditions. The analysis of that data will be reported on next quarter.

Meeting with TTI research team at College Station for the development of the detailed experimental plan

3M Research Team and the TTI research team met in College Station, TX on February 19^{th} and 20^{th}. The purpose of the meeting was to develop the detailed work plan for Task 2. The work plan was developed and sent to the FHWA AOTR.

Human Factors Pilot Study

A pilot human factors study was conducted following the installation of the pavement markings at the TTI Riverside Campus. The purpose of the pilot experiment was to identify:

i. The timings, sequence, and lengths of each subtask during the experiment for the ground crew and experimenters
ii. The general visibility assessment of each test marking under rain
iii. Consistency of rain in the rain range
iv. Feasibility of using cones to simulate a work zone
v. Any potential unforeseen issues

The general experimental setup and the pavement marking installations were found to be acceptable. Minor issues, such as slight variations in the pavement marking width in the stem sections of the markings were noticed, but the team had consensus on the minor variations as insignificant from the participant task point of view. It was also found that running each participant would take approximately one hour.

PLANNED WORK FOR THE NEXT QUARTER

Within the next quarter, we have planned for the following tasks:
Task 2 and Task 3 had been completed.

PROBLEMS ENCOUNTERED

No major problems were encountered during this quarter.

APPENDIX A-3: TASK 2 - HUMAN FACTORS FIELD EVALUATION AT TTI

HUMAN FACTORS EVALUATION OF PROTOTYPE ALL-WEATHER PAVEMENT MARKINGS UNDER DRY, WET AND RAIN CONDITIONS

The objective of this study was to evaluate the nighttime visibility of three prototype paint and dual-optics drop-on element-based all-weather pavement marking systems to determine their performance especially for work-zone applications. The nighttime visibility of the prototype pavement markings was evaluated in a dynamic driving condition under dry, wet, and raining conditions. Two commercially available pavement marking systems were also evaluated as benchmarks.

Experimental Design

The experiment was designed to simulate the nighttime driving task in a roadway work zone, and to assess the nighttime visibility of prototype all-weather pavement markings under dry, wet, and continuous rain conditions. Participants drove an experimental vehicle with low-beam headlights in a closed-course environment. The driving course included several passes through a rain-tunnel located in a Texas Transportation Institute (TTI) facility, where 0.5 inch/hour rain was generated. The participants were asked to identify the earliest point where they could detect a simulated work zone taper (and the direction of the taper). A full-factorial within-subjects design with repetitions was administered, where each participant evaluated all conditions with repetition.

Measure of Effectiveness (Dependent Variable)

The measure of effectiveness (MOE) used for this study built off of previous research. *(1,3-6)* Knowing the limitation of static evaluations, a review of dynamic evaluations was completed. Beginning and end detection tasks were considered as well as the detection of isolated skip lines. In an effort to create a work zone related visual task, this research used a MOE defined by the detection distance of a simulated work zone taper delineated exclusively by pavement markings.

Longitudinal pavement markings of varying lengths (150 to 250 ft) were installed along tangent sections of roadway. Both ends of each section of longitudinal pavement marking ended in a Y configuration with tapers to the left and right (see Figure 11). During the study only the tapers at the end of each pavement marking were shown (depending on the direction of travel) and usually only one taper was shown. However, as a way to prevent guessing, in some cases, both tapers were shown or no taper was shown. Therefore, the possible responses were: Right, Left, Both (both tapers shown), or None (both tapers were covered). The latter two responses were included solely to avoid a heuristic response. The measure of effectiveness was the distance at which a driver could correctly identify the direction of the taper. All participants viewed three repetitions of each test marking in the continuous-rainfall condition, and two repetitions of each marking treatment under the wet-recovery and dry conditions.

To form each of the tapers, the Y-configuration at the ends of each pavement marking section included 20 ft of additional pavement marking material with an angle of approximately seven degrees, resulting in a 2.5 ft offset at the end of the 20 ft taper section. Changing the configuration required temporarily covering the unused extensions with black line mask tape as shown in Figure 12. To further approximate the nighttime visual complexity in a real work zone, retroreflective delineator cones were placed at 100 foot intervals in a staggered pattern to the left and right of the travel lane as shown in Figure 12.

Figure 11. Pavement marking section as installed.

Figure 12. Pavement marking viewed at night with unused tapers masked.

Independent Variables

The key independent variables investigated in the study were the taper detection distance, the environment conditions (3 levels- dry, recovery, continuous rain), and marking types (5 levels- three prototype markings and two benchmark markings). Other variables were held constant as described below.

- Pavement marking position – all of the pavement markings used for the analysis were positioned in the center of the travel lane. This center position allowed detection distance to be collected in both directions of travel as the illuminance on the markings would be the same.

- Seat position – all the detection distances were recorded with the research test subjects driving the test vehicle and therefore from the driver's seat position.
- Ambient lighting – the experiments were conducted at night at the Texas A&M University (TAMU) Riverside Campus, which is a dark, rural environment with little ambient lighting from buildings or nearby communities.
- Recovery time - within 45-seconds and 90-seconds after cessation of rain
- Rain rate - approximately 0.5 inch/hour
- Experimental vehicle – 2004 Ford Taurus
- Headlight setting: Only-low beam headlights were used

Pavement Marking Types

Five different pavement marking treatments were tested. Three prototype all-weather marking systems were tested along with two commercial marking systems (Table 8). The prototype markings featured dual-optics elements in addition to conventional glass beads on waterborne paint. Two commercial markings, which served as benchmarks, were a standard pavement marking treatment that consisted of waterborne paint with AASHTO M247 Type 1 beads *(7)*, and a removable preformed wet reflective structured tape (3M 780 series). The markings were all white 4-inch-wide continuous lines. The standard retroreflectances of the test markings were obtained in-situ. Coefficient of reflected luminance (R_L) at the standard CEN 30-m geometry was measured under dry, rain and wet recovery conditions using a calibrated external beam retroreflectometer (LTL-X from Delta Instruments). Determination of the standardized retroreflective efficiency of the markings under dry ($R_{L\text{-dry}}$) and wet recovery conditions ($R_{L\text{-wet}}$) were conducted according to ASTM E1710 *(8)* and ASTM E2177 *(9)*, respectively. Retroreflective efficiency under actively falling rain conditions ($R_{L\text{-rain}}$) was measured according to EN1436 *(10)* using a rain simulator giving artificial rainfall, without mist or fog, at an average intensity of 0.8 inch/hour.

Table 8. Description of Prototype and Reference Pavement Marking Systems

Marking	Binder	Wet Film thickness	Optics
Prototype A	high-build waterborne paint	20	3M medium size high refractive index dual-optics drop-on elements (low drop rate; 4g/lineal ft) in combination with MODOT Type P Drop-on 1.5 index Glass Beads (12g/lineal ft)
Prototype B	high-build waterborne paint	20	3M medium size high refractive index dual-optics drop-on elements (high drop rate; 8g/lineal ft) in combination with MODOT Type P Drop-on 1.5 Glass Beads (12g/lineal ft)
Prototype C	high-build waterborne paint	25	3M large size high refractive index dual-optics drop-on elements (high drop rate; 8g/lineal ft) in combination AASHTO M247 Type 1 Drop-on 1.5 index Glass Beads (12g/lineal ft)
Benchmark 1	high-build waterborne paint	15 mil	AASHTO M247 Type 1 Drop-on 1.5 index Glass Beads
Benchmark 2	Preformed structured tape	NA	Specially designed optics to provide high retroreflective efficiency in dry and wet conditions (3M™ Stamark™ Wet Reflective Removable Tape Series 780)

Participants

Thirteen men and seventeen women participated in the study. All study participants but one (55 years of age) were over 60 years of age. Ages ranged from 55 to 80, with an average age of 69. All participants possessed a valid driver's license. Participants were met at the entrance to Texas A&M University (TAMU) Riverside campus and taken to an office for a prescreening. During the prescreening, they completed an Informed Consent form and a demographics questionnaire, then underwent the Snellen Eye Chart test for visual acuity, the Functional Acuity Contrast Test (F.A.C.T.), and the Ishihara Color Test. Twenty-eight participants were found to have Snellen visual acuity scores of 20/25 or better; twenty-six scored 20/25 or better on the F.A.C.T. test. One participant's Snellen score indicated 20/30 vision, but the F.A.C.T. score was 20/20; three participants scored 20/30 on the F.A.C.T. test but had Snellen acuity scores of 20/25 or 20/20. One participant had 20/40 vision, as measured by both the Snellen and F.A.C.T. tests. The Ishihara test confirmed that all participants had normal color vision.

Experimental Equipment and Facilities

A 2004 TTI Ford Taurus with HB5-halogen headlamps was used as the test vehicle (see Figure 13). All measured data were collected with the participant driving approximately 30 mph. The vehicle was equipped with the following: (1) a special control switch on the passenger side that allowed the researcher to control the windshield wipers, and (2) a distance measuring instrument (DMI) for recording detection distances of the pavement marking samples (see Figure 14). During the test runs, the windshield wipers were set to high during both the rain and the wet recovery conditions. The researcher sitting in the passenger seat recorded the DMI readings and used a used a radio to communicate with field staff.

Figure 13. Ford Taurus used as study vehicle

a) DMI, Data Sheet, and Radio	**b) Wiper Switch**

Figure 14. Test equipment

To produce the dry, wet, and continuous-rainfall conditions, each pavement marking system was installed at two locations within the TAMU Riverside Campus. One set of markings was installed on Avenues A and B for evaluation under dry conditions. The second set of markings was installed on the TTI Rain Range, which is fitted with rain nozzles cantilevered over the roadway. The rain range located on Bryan Road was used to generate the artificial rain and wet conditions simulating immediately after a rain event (also known as wet-recovery condition). A driving route was selected to minimize the probability of a heuristic (i.e., learning) effect on detection distances.

Figure 15 illustrates a section of the rain range showing the equipment used to produce artificial rain. For the wet recovery condition, the system was turned on for at least one minute to fully wet the roadway, then turned off. The study participants were instructed to enter the rain tunnel approximately one minute after the rain was turned off.

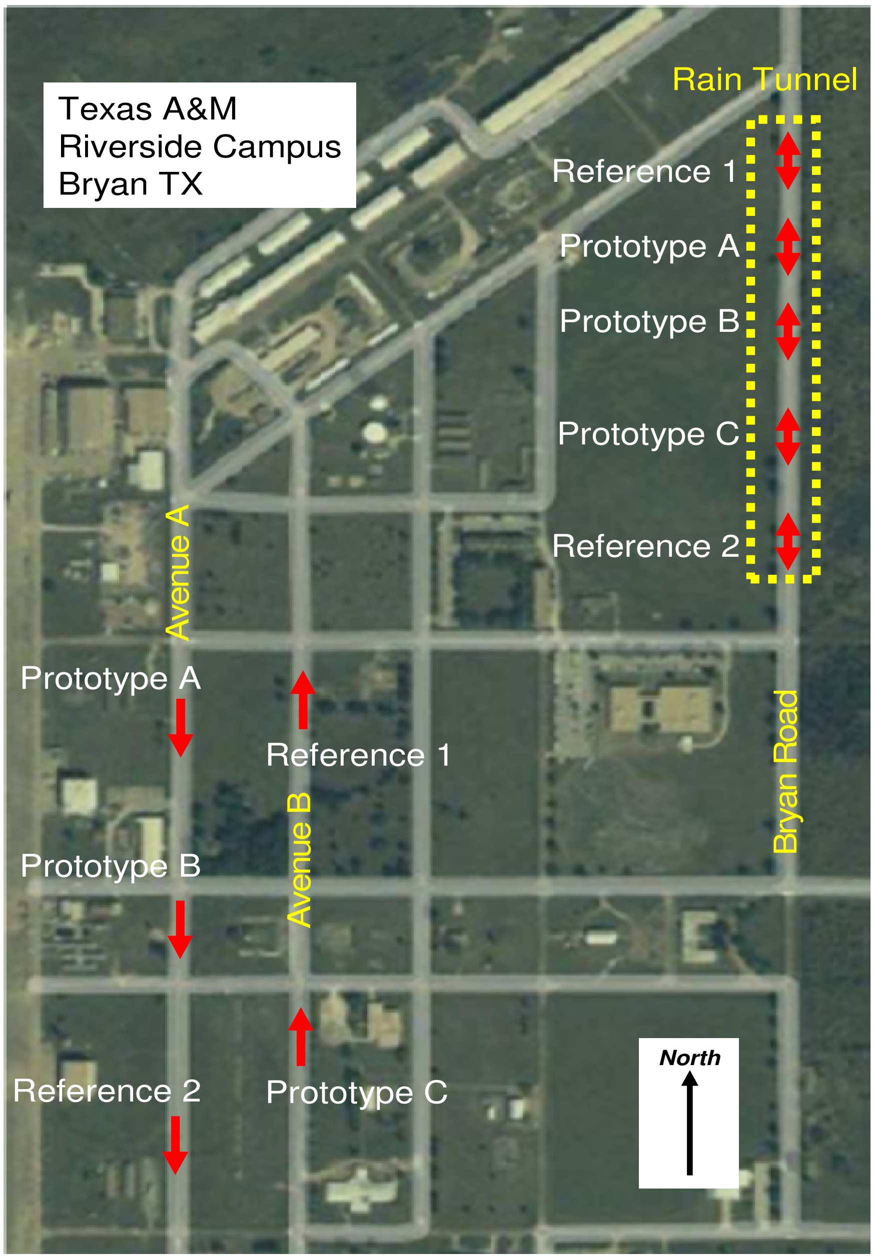

Figure 15. Experimental test course layout.

The rainfall area in the TTI rain tunnel is approximately 14 feet in width, or slightly over one standard driving lane wide. Pavement markings were installed in the middle of the rainfall lane to allow test subjects to drive the rain tunnel and view the test markings from both directions (this keeps the amount of headlamps illumination consistent in both direction). For consistency, the markings were also placed in the center of the driving lane on the "dry" test sections located on Avenues A and B.

Figure 16. Close up view of sprinkler system used to produce artificial rain on the TTI Rain Tunnel, viewed from north end of Bryan Road.

STUDY PROCEDURE

Two to three study participants were run per night. The study required 45 to 60 minutes to complete. The participants were paid $40.00 for completing the study.

Participants were told they would be evaluating pavement markings prior to the driving task, and given brief instructions regarding the study procedure. Each participant was then led outside to the test vehicle where they were allowed to adjust the driver's seat, mirrors and acquaint themselves with the vehicle. After the participant was comfortable they drove the vehicle to a test section to allow the participant to become familiar with the experimental protocol. Although the participants had reasonably good vision, failure in any one of the vision tests would not have disqualified them from participating. The vision tests were conducted to identify any vision defects for consideration in the data analysis.

Once a participant was familiar with the test vehicle and the experimental procedure, they were instructed to drive the experimental route at a speed of approximately 30 mph. The research team followed the general guidelines listed below:

- Data collection began after astronomical twilight.
- Each time the test vehicle exited the rain tunnel, a field crew reconfigured the tapers in accordance with the preset experimental plan prior to the re-entry into the rain tunnel.

- The order of environmental conditions was counterbalanced between participants. .
- When viewing a test segment, the participant was instructed to state aloud as soon as they could identify whether there was a taper to the left, to the right, in both directions, or straight. The researcher recorded the DMI distance value at the time of the participant's response.
- Several reference points were set throughout the course to stop the vehicle and reset the DMI. The distance to a test treatment section from its associated reference point was used to calculate taper detection distances from the observational DMI data. These reset points also provided opportunities to answer participant questions, to break up the testing to minimize heuristic responses as well as minimize any compounding of DMI measurement errors.
- The research protocol required testing to be suspended in the event of natural rain or high winds.

DATA ANALYSIS

Data were reduced into an Excel spreadsheet for further analysis. DMI distances recorded on the datasheets were manually entered along with the demographic information for each study participant and the marking layouts for each test section. The taper detection distances were calculated from the DMI recorded distances and the distance from the reference DMI reset point to the appropriate test marking.

Table 9 contains the descriptive statistics for all five pavement marking treatments grouped by the three environmental conditions (i.e., dry, wet-recovery, and continuous-rainfall). The sample sizes within each condition are the same across all marking treatments. Some data were lost due to equipment failures. However, relative to the number of missed responses (i.e., taper not reported) by study participants, the number of missing data points was negligible. It should be noted that the sample sizes for Benchmark 1 (conventional paint and beads) in the wet recovery and rain conditions are low because a significant portion of the study participants failed to detect the tapers constructed with this pavement marking system. A few missed responses were likely due to simple human error on the part of the study participant or the researcher, and with the exception of Benchmark 1, no driver missed any individual marking more than once. The Benchmark 1 treatment in the rain range was notable as the treatment to which study participants most often failed to respond (i.e., they did not see the marking at all).

If a participant did not provide a response to a marking, the researcher in the vehicle noted the missed response but did not inform the participant of the missed marking, since (to avoid biasing the responses) participants were not informed of the number of markings to expect on each run. Additionally, some participants identified the taper direction for a marking belatedly on one or more viewings, realizing that they had seen the marking only after the vehicle had already passed it. These late responses resulted in "detection distances" that were negative numbers. In the data analysis, the research team counted these belated responses as additional missed responses, since a driver detecting a real-world roadway curvature or obstacle after the vehicle has reached/passed it would be in as much danger of an accident as if he or she did not detect it at all. Table 10 summarizes the data points that were categorized as missed markings in the data analysis. The Benchmark 1 treatment was missed (not seen or identified late) 22 times in the wet recovery condition, and 54 times in the rain condition.

Table 9. Taper Detection Distance - Descriptive Statistics.

Environmental Condition	Marking System	Sample Size	Detection Distance (ft)			
			Minimum	Mean	St dev of Mean	Maximum
Dry	A	57	102	272.7	64.0	419
	B	57	86	199.1	51.9	341
	C	60	79	221.0	56.6	325
	Benchmark 1 (conventional paint and beads)	60	58	199.8	46.7	279
	Benchmark 2 (wet-weather tape)	57	63	285.0	73.3	408
Wet Recovery	A	60	58	170.4	56.3	276
	B	60	40	161.3	57.3	304
	C	58	51	156.2	47.9	262
	Benchmark 1	37	8	55.5	32.4	130
	Benchmark 2	60	43	181.9	55.5	346
Rain	A	111	8	134.4	50.5	257
	B	114	15	135.0	49.9	299
	C	113	45	131.2	42.4	256
	Benchmark 1	58	1	34.7	20.7	79
	Benchmark 2	114	10	147.0	45.2	289

Table 10. Missed and belated responses to markings.

Environmental Condition	Marking System	No Response	Belated Response (after vehicle had passed marking)
Wet Recovery	C	1	1
	Benchmark 1	15	7
Rain	A	2	1
	C	-	1
	Benchmark 1	38	16

Figure 17 shows the average taper detection distances for each pavement marking system under the three environmental conditions. Error bars represent ±1 standard deviation from the mean. The results of a one-way ANOVA are presented in Table 11 in terms of Tukey's HSD (Honestly Significant Differences) Test. Overall, the dry conditions provided the longest detection distances, followed by wet recovery, then continuous rain conditions. Under the dry condition, the performance of prototypes B, C and Benchmark 1 were not statistically different from each other. Prototype A and Benchmark 2 (wet-weather tape) were also not statistically different from each other under dry conditions and both were different from the other two prototypes and Benchmark 1. The nighttime visibility properties of prototypes A, B, and C were not statistically different from one another or were they different from the Benchmark 2 under either the wet recovery or rain conditions. The detection distance for Benchmark 1 was significantly shorter in both the wet and rain conditions than the other marking systems evaluated.

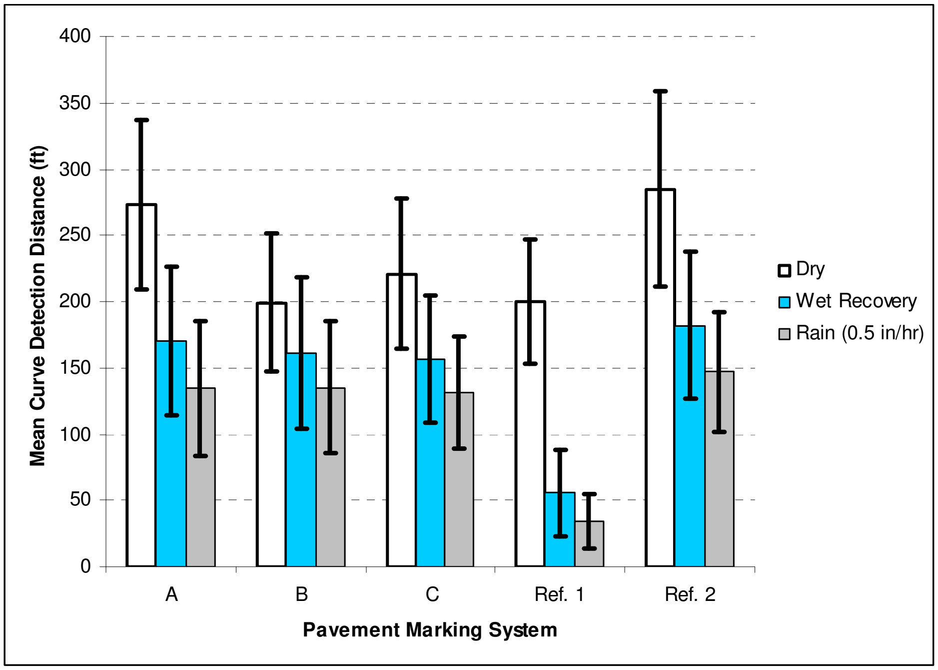

Figure 17. Mean Taper Detection Distance as a function of Pavement Marking System and Environmental Condition.

Table 11. Tukey HSD Test Results.

Condition	Marking Treatment	Sample Size	Detection Distance (ft)	
			Group 1	Group 2
Dry	B	57	199	
	Benchmark 1	60	200	
	C	60	221	
	A	57		273
	Benchmark 2	57		285
Wet Recovery	Benchmark 1	37	56	
	C	58		156
	B	60		161
	A	60		170
	Benchmark 2	60		182
Rain	Benchmark 1	58	35	
	C	113		131
	A	111		134
	B	114		135
	Benchmark 2	114		147

The retroreflective efficiency of each marking was measured using standard test protocols corresponding to the appropriate environmental conditions under which the marking were viewed - dry, wet recovery, and continuous rain (Table 12). The retroreflectivity was measured periodically throughout data collection to assess any changes that might bias the results. Data presented in Table 12 show that the retroreflectivity of the markings was stable during the study.

Table 12. Coefficient of Retroreflected Luminance (mcd/m^2/lx; CEN 30 m geometry)

Weather Condition	Statistic	Prototypes			Benchmarks	
		A	B	C	1	2
Dry markings (per ASTM E1710)	Avg	520	547	532	284	866
	Stdev	67	44	66	26	155
(average change from 4/28/2008 to 5/20/2008)		0%	-4%	4%	5%	3%
Wet markings (per ASTM E2177[a]; 45 sec recovery)	Avg	628	545	407	13	611
	Stdev	178	139	70	11	69
Rain markings (per EN 1436[b]; 5 min rain @ 0.8 in/hr)	Avg	520	433	328	17	575
	Stdev	198	94	82	10	78

[a] ASTM E2176 requires "..wet the area of the marking to be measured and the adjacent surrounding area (road surface and marking) for 30 s…Measure the coefficient of retroreflected luminance, R_L, of the wetted marking 45 ± 5 s after completion of spraying.."
[b] EN 1436 requires "..artificial rainfall, without mist or fog, at an average intensity of (20 ± 2) mm/h [0.79 ± .08 in/hr] …R_L in condition of rain shall be made after 5 min of continuous rain…while rain is falling."

FINDINGS

The findings of the visibility study of the three prototype all-weather work zone pavement markings are summarized below.

- On average, the removable wet-reflective tape provided the longest detection distances (Benchmark 2), and the paint with conventional glass-bead optics (Benchmark 1) provided the shortest detection distances.
- In all three environmental conditions, Benchmark 2 and Prototype A performed the best, in other words had the longest detection distances which were statistically equivalent to one another.
- In both the continuous rain and wet-recovery conditions, all three Prototypes and Benchmark 2 had statistically the same detection distances which were statistically longer than Benchmark 1 (conventional glass-bead optics).

- In the dry condition, Benchmark 2 and Prototype A had statistically the same detection distances, which were statistically longer than Prototypes B and C and Benchmark 1.
- Markings with dual-optics designed for wet weather conditions are less impacted by rain than conventional glass bead markings.
  - Under the wet-recovery condition, the all-weather paint prototypes (and Benchmark 2 – the tape designed for wet weather conditions) sustained average detection distances at 60-80 percent of their dry values, while Benchmark 1 (a conventional glass bead marking) provided only 28 percent of its dry detection distances.
  - Under the continuous rainfall condition, the all-weather paint prototypes (and Benchmark 2) sustained average detection distances at 50-70 percent of their dry detection distances, as opposed to 17 percent for Benchmark 1.
- Tapers marked with conventional markings were missed (not detected) by nearly half of study participants in the rain and by nearly one-third under wet-recovery conditions. The tapers marked with the experimental all-weather paint markings or wet-reflective tape markings were visible to all the drivers under all conditions.

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9. ASTM, International, ASTM E2177-01:"Standard Test Method for Measuring the Coefficient of Retroreflected Luminance (R_L) of Pavement Markings in a Standard Condition of Wetness," West Conshohocken, PA, 2001.

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PHOTOMETRIC CHARACTERIZATION OF TEST MARKINGS UNDER DRY AND RAIN CONDITIONS USING A CALIBRATED CCD PHOTOMETER

Field measurements were made of the test markings luminance at the TTI Rain Tunnel to characterize the properties of each marking system in the actual on-road installation. The measurements were made using a calibrated imaging photometer (Radiant Imaging ProMetric Imaging Photometer Model PM-1413E-1) equipped with a variable zoom lens. Measurements were made from the driver point of view from within the test vehicle with illumination provided by the vehicle low beam headlights. The measurements were made only on the test marks installed within the TTI Rain Tunnel to allow direct comparisons of each system under both dry and rain conditions. All five test markings were measured on the road under dry conditions, but only four were measured in the rain. The TTI Rain Tunnel is divided into two zones in order to be able to provide consistent artificial rain over its entire 1600 ft length. During the measurements in rain one of the pipes feeding the south zone broke requiring TTI to shut this zone off. Measurements of Reference 1 and Prototype C, which were located within the south zone, had been completed before the south zone failed. The north zone was unaffected and we were able to do Prototype A and Reference 1 in the rain. We were not able to conduct measurements on Prototype B in the rain because it was situated half in each of the two rain zones. The south rain zone was repaired and operational prior to the start of the human factors runs.

Luminance measurements were made at three distances (60m, 45m and 30m) to produce a photometric profile of each line. The 30m distance was chosen to correspond to the measurement geometry called for in the standard instrumental test protocols for coefficient of retroreflected luminance (R_L). The luminance measurement location for each marking was the junction point of the Y-configuration where the tapers branched out from the main line at the ends of each test pavement marking section. Measurements were also made of the pavement adjacent to the marking to be used for calculating the contrast between the respective markings and the pavement. The road surface upon which the test markings were installed was not optically flat, but rather had the bumps and unevenness typical of a normal public roadway. Those normal road surface "imperfections" can influence the illumination received from the test vehicle at each location. We used diffuse reflective targets next to the measurement location to quantify the illumination at each measurement location (Figure 18). Under the dry condition we also made illuminance measurements using a Minolta T-10 handheld illuminance meter (Figure 19). For the rain measurements only one diffuse reflective target was used for reference (Figure 20).

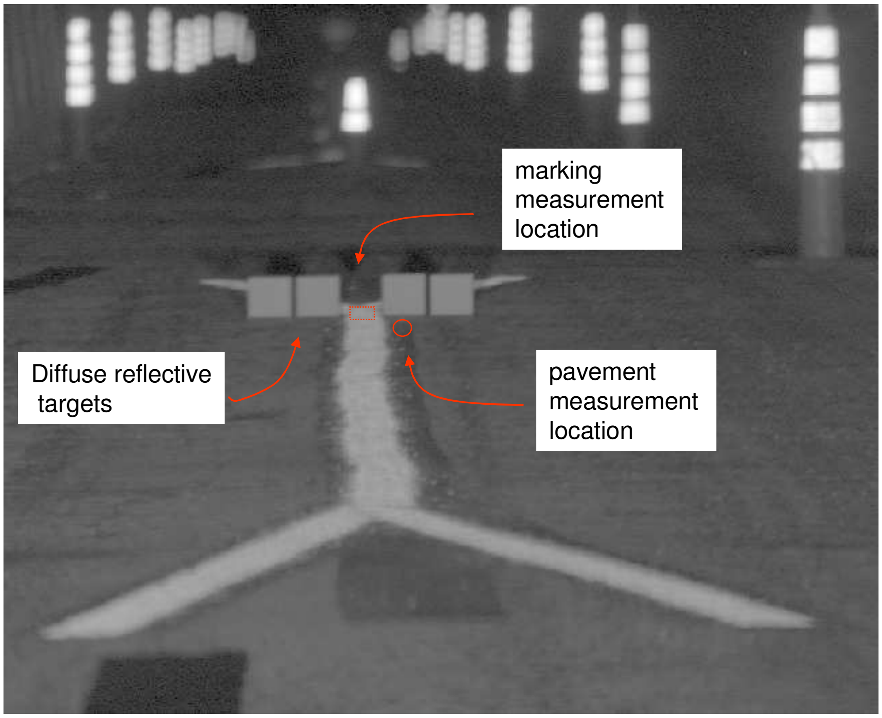

Figure 18. Screen capture from imaging photometer showing the locations of the reference luminance measurement location and set-up for the diffuse reflectance targets under dry conditions.

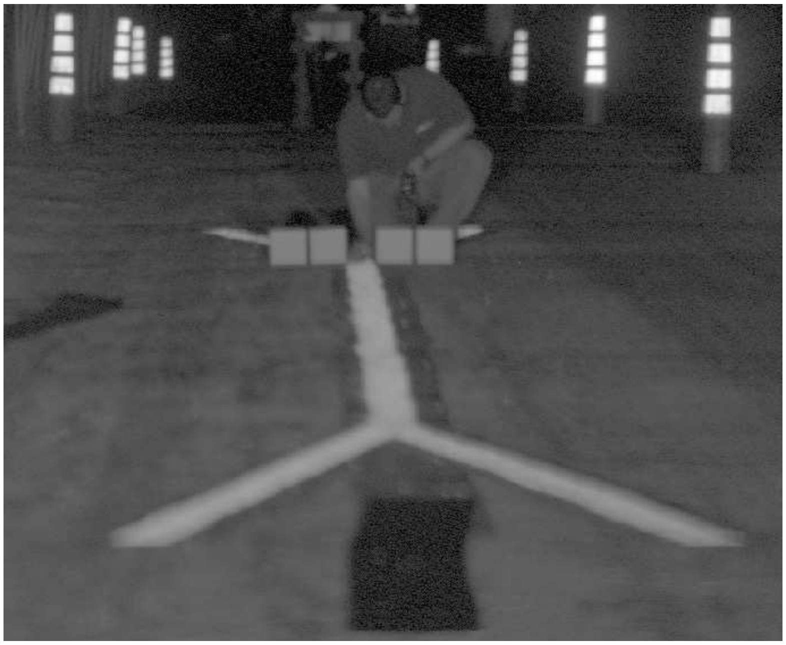

Figure 19. Illustration of illuminance measurement using the handheld illuminance meter.

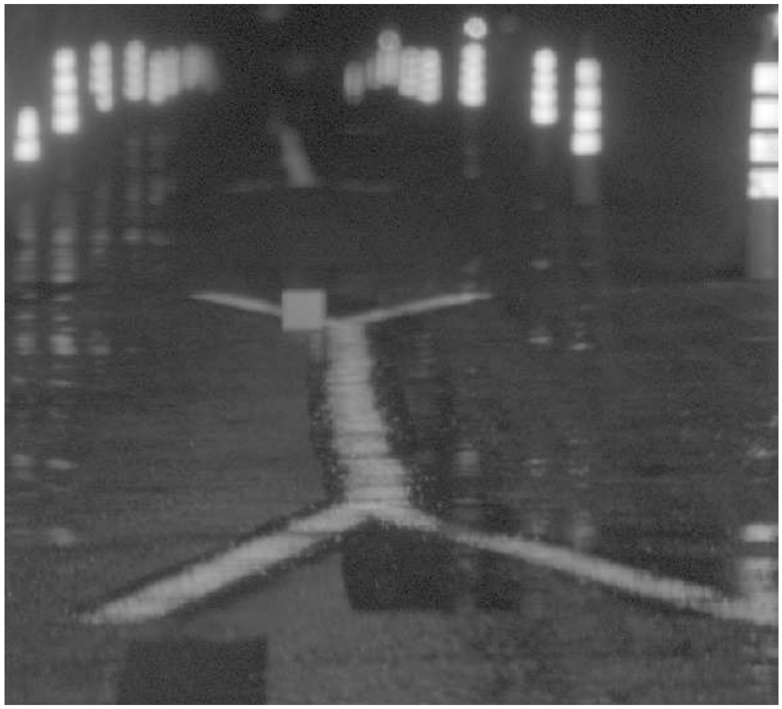

Figure 20. Screen capture from imaging photometer showing set-up for the diffuse reflectance targets under rain conditions.

The following are a series of plots showing the results of the photometric measurements.

DRY RESULTS:

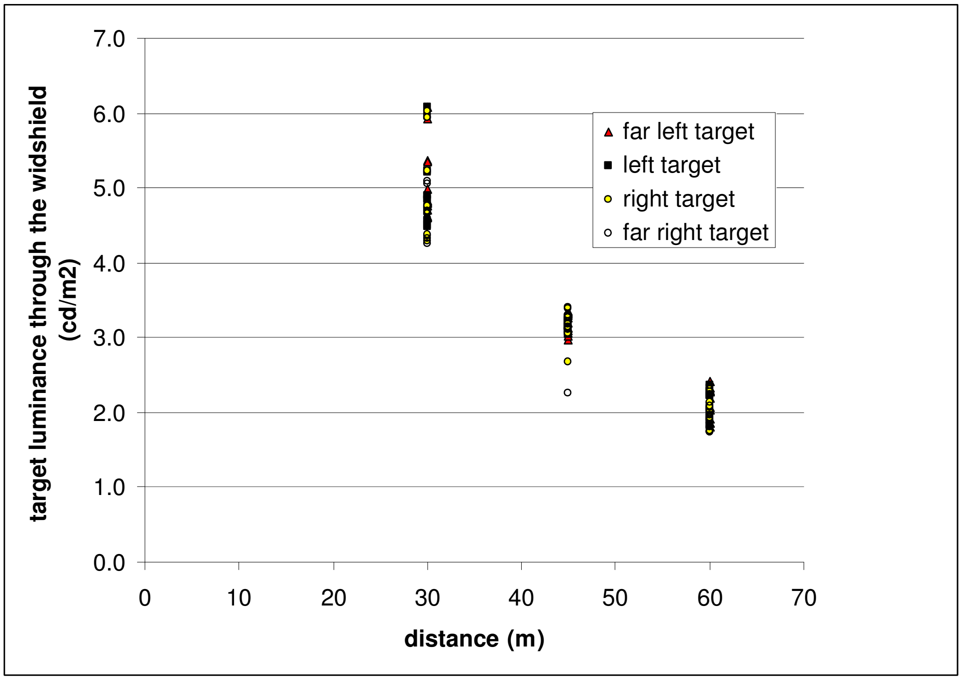

Figure 21. Diffuse target luminance from the driver point-of-view through the windshield as a function of distance and position on the road (dry conditions).

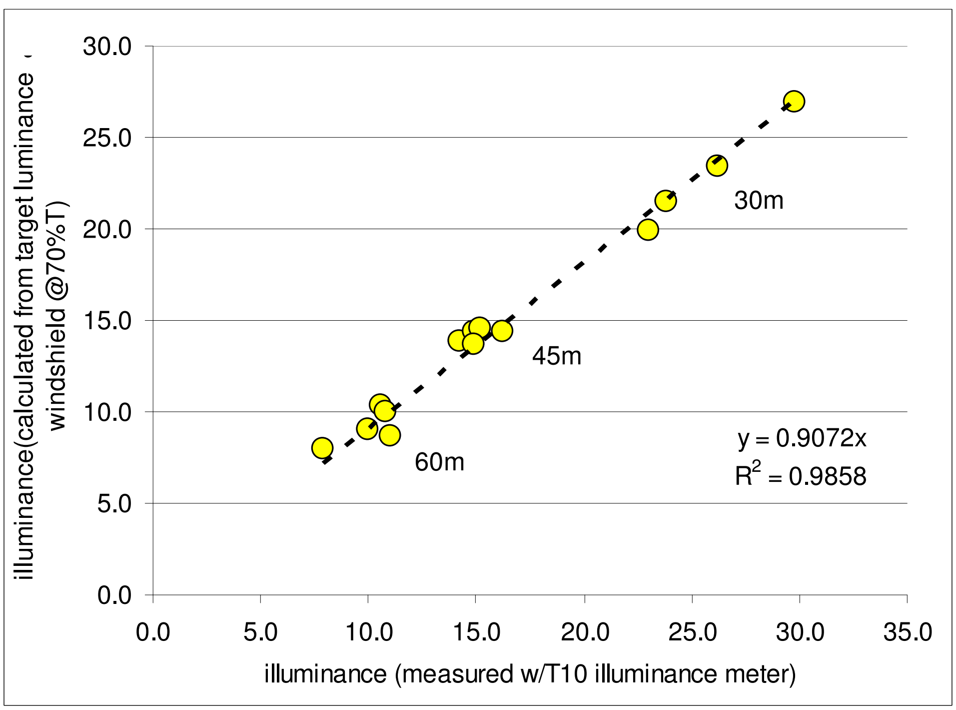

Figure 22. Correlation between the total illuminance from the vehicle headlights measured with the handheld luminance meter and total illuminance calculated from the average luminance of the right & left diffuse target, corrected for the transmission of the windshield (dry conditions).

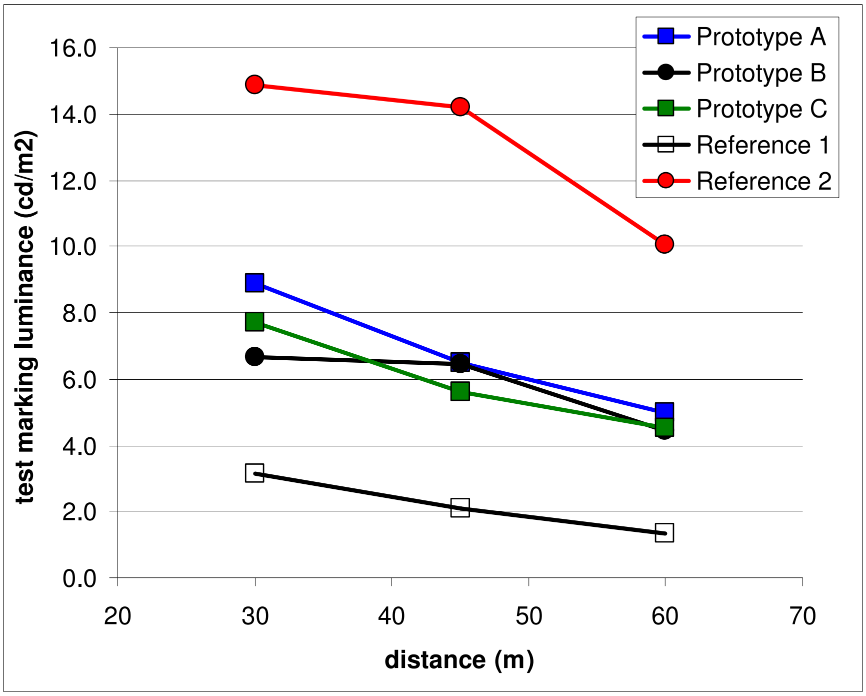

Figure 23. Test marking luminance from the driver point-of-view through the windshield as a function of distance (dry conditions).

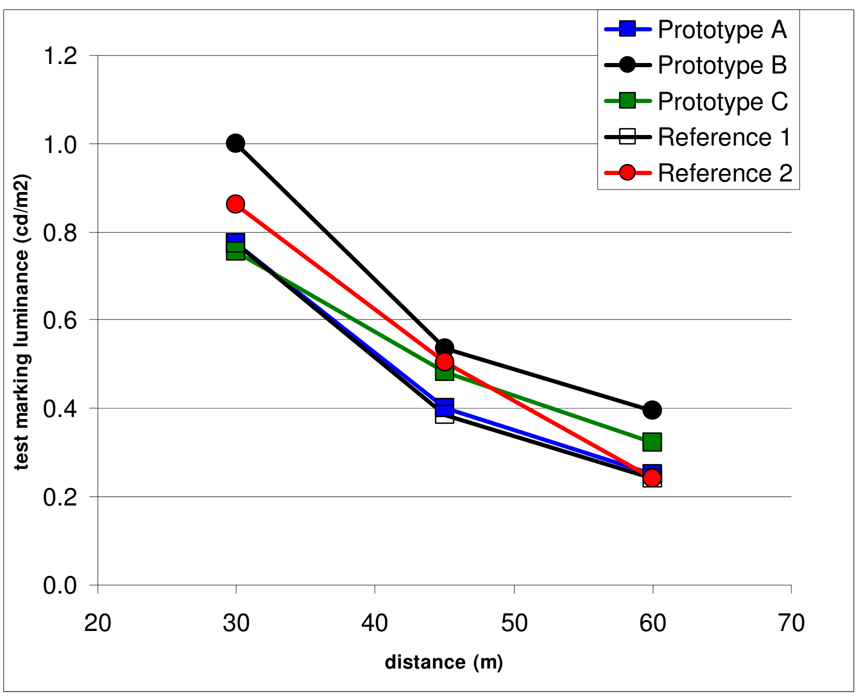

Figure 24. Luminance of the roadway surface adjacent to the test marking from the driver point-of-view through the windshield as a function of distance (dry conditions).

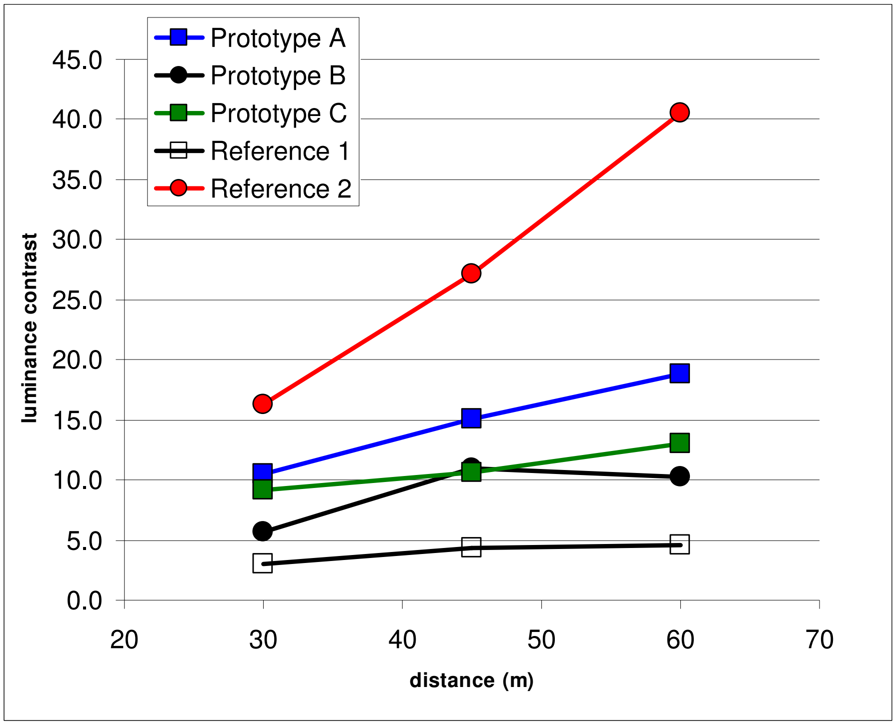

Figure 25. Luminance contrast between the test marking and the adjacent roadway surface as a function of distance (dry conditions, Contrast = (Lmarking-Lroad)/Lroad).

RAIN RESULTS

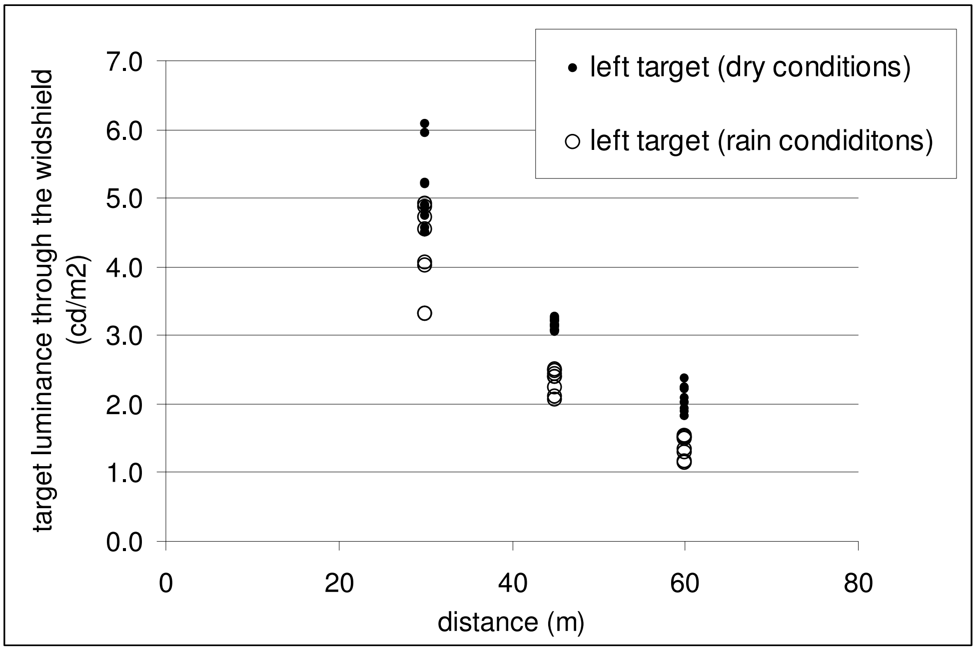

Figure 26. Diffuse target luminance from the driver point-of-view through the windshield as a function of distance, position on the road and conditions (dry versus rain conditions).

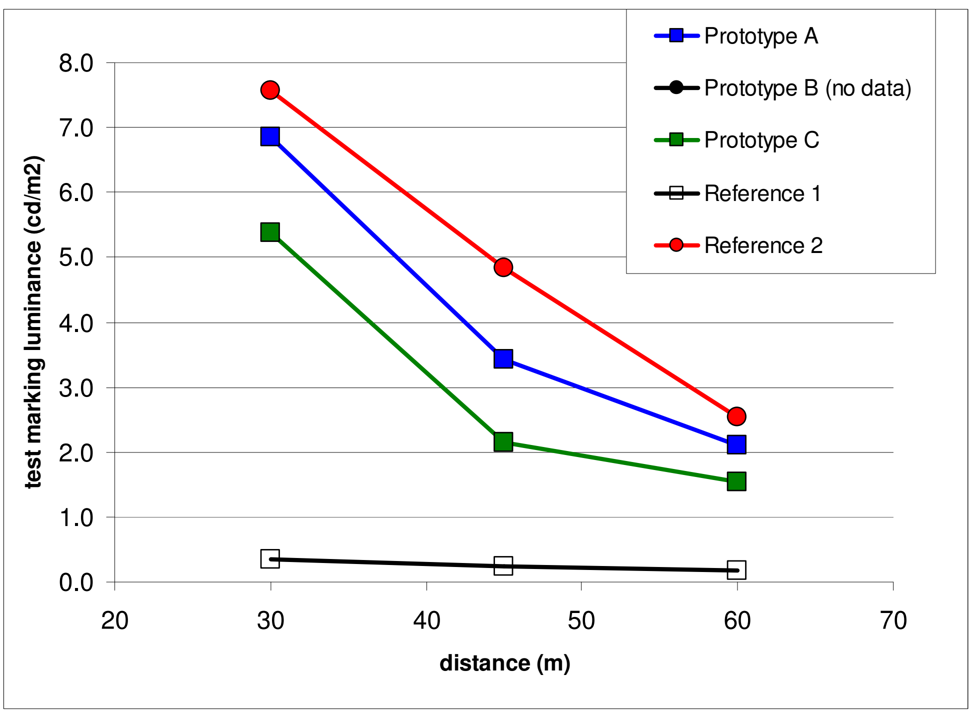

Figure 27. Test marking luminance from the driver point-of-view through the windshield as a function of distance (rain conditions).

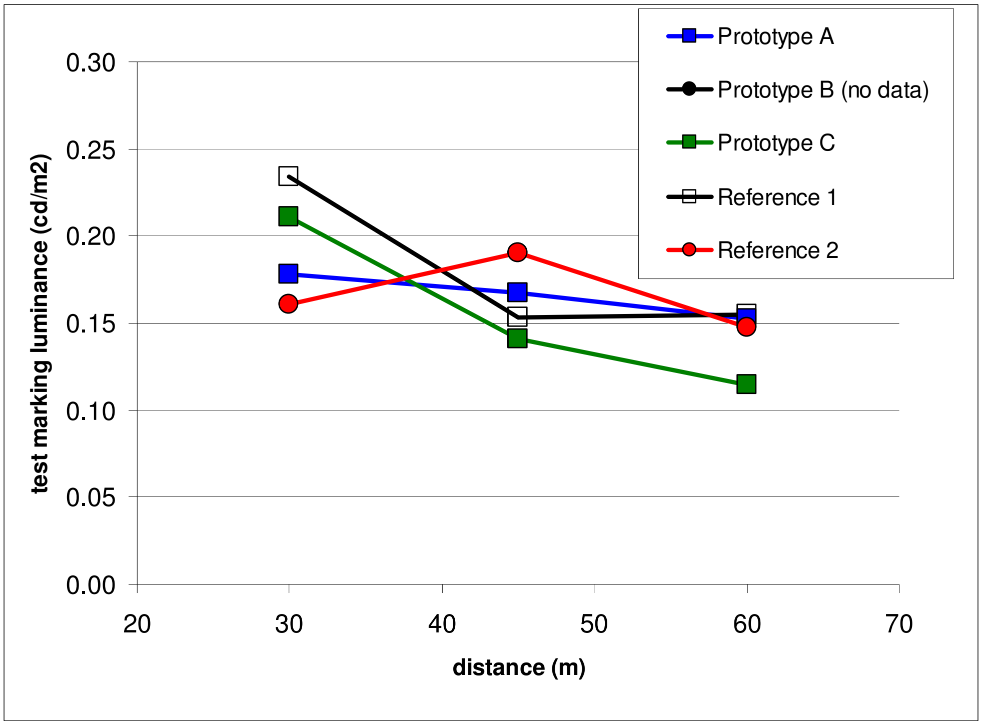

Figure 28. Luminance of the roadway surface adjacent to the test marking from the driver point-of-view through the windshield as a function of distance (rain conditions).

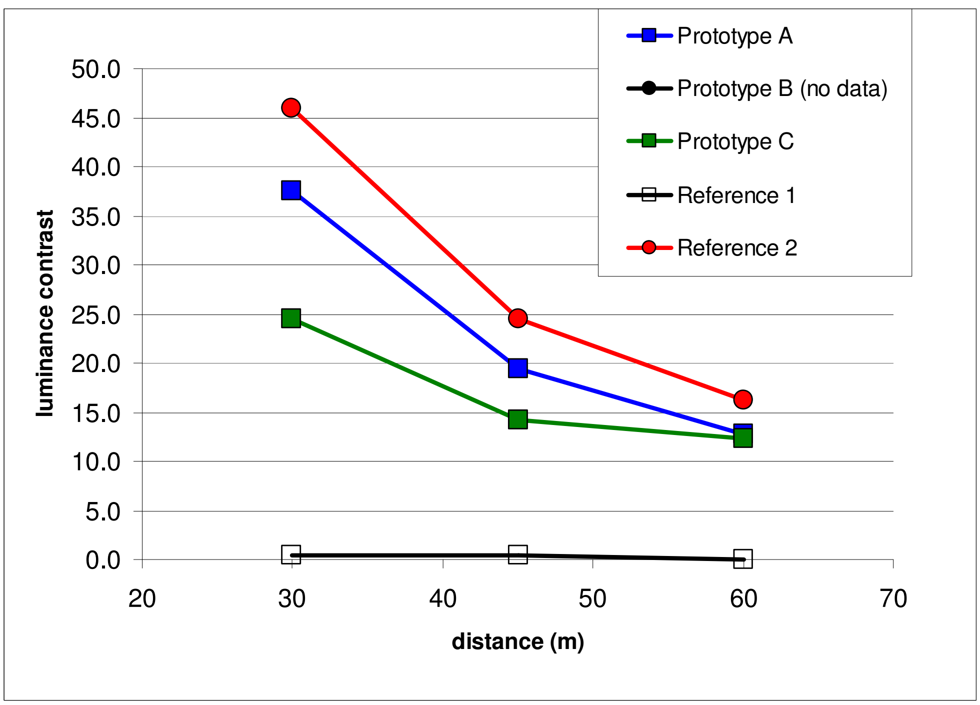

Figure 29. Luminance contrast between the test marking and the adjacent roadway surface as a function of distance (rain conditions, Contrast = (Lmarking-Lroad)/Lroad).

Figure 30. Screen captures from imaging photometer showing Prototype A at a distance of 45m under dry (left) and rain (right) conditions.

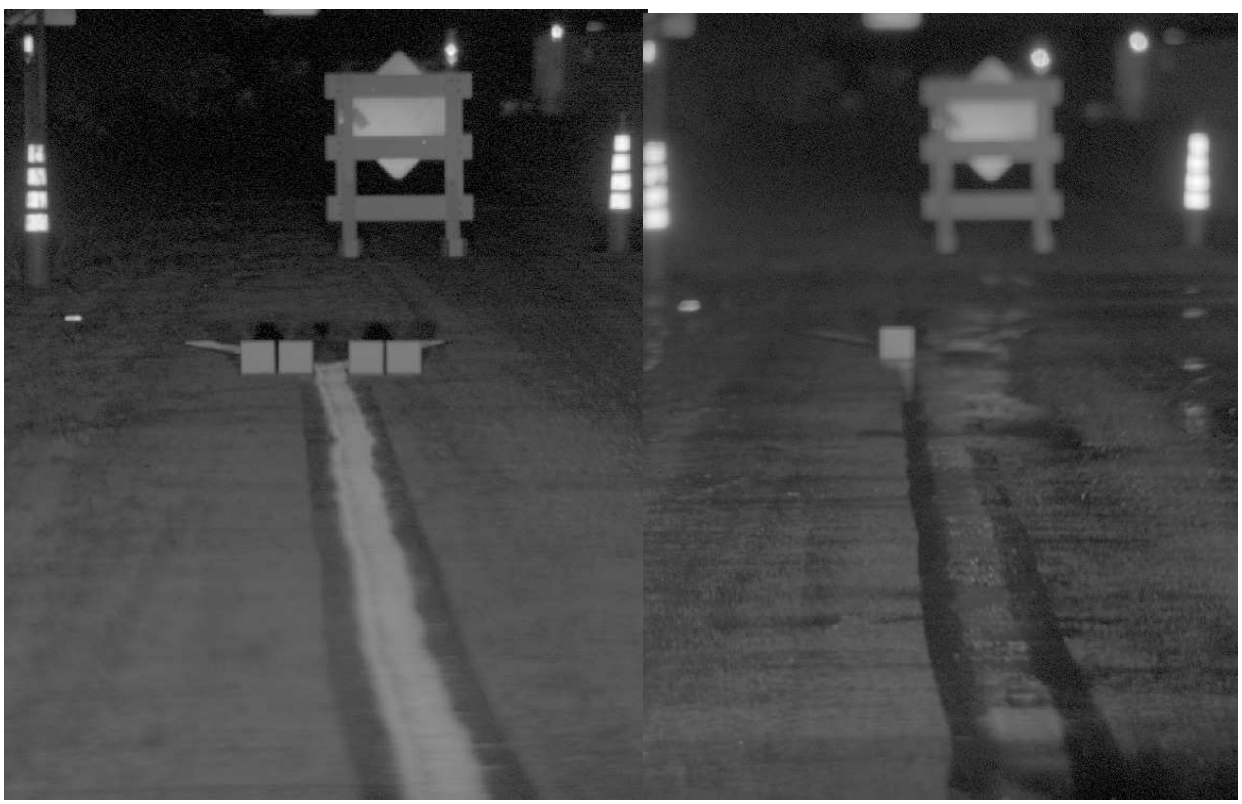

Figure 31. Screen captures from imaging photometer showing Reference 1 at a distance of 45m under dry (left) and rain (right) conditions.

APPENDIX B: PRELIMINARY WORK PLAN FOR PHASE II

Phase I – Task 3: Coordination and logistical planning for field work-zone evaluation for Phase II

INTRODUCTION

In Phase II, 3M plans to evaluate the effectiveness of the all-weather work zone pavement marking system (experimental treatment), as well as traditional paint and bead pavement markings (control treatment) at night during wet-weather in actual work zones. This technical memorandum contains the general experimental plan for these field studies. A more detailed experimental plan is to be developed in Phase II prior to the conduct of the field studies (as per the original proposal for this project).

DESIRED WORK ZONE CHARACTERISTICS

In work zones, unexpected changes in the roadway alignment, such as lane shifts and crossovers, may be challenging to drivers at night during wet-weather conditions since conventional pavement markings seem to disappear. Visible pavement markings under wet-weather conditions would continue to provide critical path guidance information and thus may reduce driver workload and in turn improve safety compared to conventional pavement markings. TTI researchers recommend that the two pavement marking treatments be applied in lane shifts since a minimal number of additional visual cues from other traffic control devices are typically present at these types of locations. Lane shifts that require greater changes in alignment (i.e., those with larger degrees of curvature and lateral offsets) are preferred. When existing pavement marking materials are removed in order to create a lane shift, the removal method typically leaves "ghost" markings which may be mistaken for actual pavement markings and thus cause confusion to drivers. Thus, lane shifts with "ghost" markings that do not align with the lane shift path are desired. TTI researchers believe that these types of conditions will maximize the potential to detect a benefit from the all-weather work zone pavement marking system.

Crossovers may also be used, if necessary. However, additional path guidance is typically provided by various other traffic control devices upstream and throughout the crossover (e.g., arrow panels at the upstream lane closure point, high target channelizing devices (drums), chevrons, etc.). Thus, the potential to detect a benefit from the all-weather markings is more likely to be diminished at these types of locations.

The field studies should be conducted on high-volume, multilane, divided roadways with a normal (non-work zone) posted speed limit ≥ 55 mph. Higher-volume roadways will result in greater numbers of vehicles traveling at night, which is the user group of primary interest in this type of study. Other variables that may impact the effectiveness of the all-weather work zone pavement marking system are type of roadway surface (asphalt versus concrete) and whether or not ambient lighting is present (existing high-mast lighting or temporary lighting for the work zone).

Table 1 contains the desired site matrix. At a minimum, TTI researchers recommend that the two pavement marking treatments be evaluated at four sites (i.e., one site per cell in Table 1). To increase the validity of the field studies, TTI suggests increasing the number of sites to eight (i.e., two sites per cell in Table 1).

Table 1. Desired Site Matrix. [a]

Roadway Surface	Ambient Lighting	
	Not Present	Present [b]
Asphalt	X	X
Concrete	X	X

[a] Assuming all sites are on high-volume, multilane, divided roadways with a normal posted speed limit ≥ 55 mph.
[b] Could be existing high-mast lighting or temporary lighting for the work zone

EXPERIMENTAL PLAN

Study Design

At each work zone, researchers will evaluate the effectiveness of the all-weather work zone pavement marking system (experimental treatment) and traditional paint and bead pavement markings (control treatment) at night during wet-weather using operational measures as surrogates for safety. There are two types of study designs that could be used. The first is a before-and-after study in which both types of pavement markings are applied at different times at the same location in the work zone. While it will take longer to collect data at each site, using the before-and-after study approach significantly reduces the site-to-site variability that would be present in the data. Higher variability diminishes the ability to detect a difference between treatments. The second method would be to apply the two pavement marking treatments at the same time in different locations in the same work zone (e.g., one treatment located at the beginning of the lane shift and one treatment located at the end of the lane shift or if available, at the beginning of the lane shift in the opposite direction). While in theory this method reduces the amount of time needed to collect data at each site, the site differences themselves confound with the effects that the different pavement marking treatments may have, making it more difficult to detect actual differences between the pavement marking treatments in terms of their effect on the operational measure of effectiveness. In addition, if the sites are far apart the rainfall events at each location may vary considerably; and thus, actually increase the time needed to collect an adequate amount of data for each condition.

Based on the discussion above, TTI researchers recommend the use of the before-and-after study design. Typically, researchers will evaluate the control treatment in the before time period and the experimental treatment in the after time period. However, if more than one site per cell in Table 1 is used, at one site the control treatment (i.e., traditional paint and beads) should be evaluated first, and at the second site the experimental treatment (all-weather work zone pavement marking system) should be evaluated first. It should also be noted that since data will be collected at multiple work zones, the effect of the experimental treatment could still be confounded with the effect of uncontrollable extraneous variables that change between the before and after time periods. Comparison sites where no experimental treatment is applied are often used to help ensure the internal validity of the study by reducing confounding effects; however, finding work zones that are comparable to the study sites is almost impossible due to the vast assortment of work zone and roadway characteristic combinations. Thus, comparison sites are rarely used with this type of work zone study. Furthermore, given that the before and after time periods being proposed are likely to be fairly short and one right after the other, the potential for significant changes in the extraneous variables over both periods is likely to be minimal.

Data Collection

At a minimum, researchers should collect the following for each treatment at each site:

- the lateral placement of vehicles in the outside travel lane;
- rainfall data (e.g., amount and duration);
- pavement marking maintained presence;
- pavement marking retroreflectivity; and
- roadway and work zone characteristics.

The lateral placement data should be collected at three locations: immediately upstream of the lane shift (base location), at the midpoint of the first curve, and at the mid-point of the second curve. Since past studies (*1, 2*) have not shown a strong correlation between speed and delineation treatments, TTI does not believe it is worthwhile to collect vehicle speed data in the lane shift itself. However, vehicle speed data should be collected immediately upstream of the lane shift and compared amongst pavement marking treatments at each site and across sites to determine if the traffic characteristics were similar for all conditions or may have been affected by uncontrollable extraneous variables. Lateral placement and speed data should also be collected under dry pavement conditions (both at night and during the day) to help identify any unrelated conditions that might have affected the nighttime, wet-weather data.

Sample Size

TTI researchers determined the sample size (the number of vehicles) needed to detect a practically important minimum difference between pavement marking treatments and among the interaction effects between the pavement marking treatment and the weather factor (wet or dry) at each site by power analysis. The procedures given in Wheeler (*3*), Nelson (*4*), and Bratcher et al. (*5*) were used for the sample size calculation. Because the necessary sample size varies with the desired significance level (α), the desired power, the standard deviation of the response variable, and the minimum difference of practical importance, those values were predetermined before the sample size calculation. By convention, the desired significance level and the desired power were set to 0.05 and 0.90, respectively. It was found from previous research, that the approximate standard deviation in lateral placement in the curves was 20 inches (*6*) and in work zones was 13 inches (*7*). To err on the conservative side, 20 inches was used. The minimum difference of interest before and after installation of the all-weather work zone pavement marking system was determined to be 6 inches for the mean lateral placements based on engineering judgment and previous research (*6*). It is believed that 6 inches is the minimum change in mean lateral placement that would be a practically significant change for at least two reasons: (1) field experience has shown that striping installations vary in width as much as ±0.5 inches and restriping can be misaligned by more than one inch, which may result in wide variability between pavement marking installations; and (2) previous research supported 6 inches (*6*).

The following equations were employed to determine the minimum sample size when the desired significance level is 0.05 and the desired power is 0.90. Equation 1 is used to detect main effects due to pavement marking treatment or the weather factor and Equation 2 is used to detect an interaction effect between pavement marking treatment and the weather factor.

$$n = \left(3r\sigma/\Delta\right)^2 \tag{1}$$

From Equation 1, r is the number of levels of a factor, σ is the standard deviation of the observations, and Δ is the minimum difference of importance between any two main effects.

$$n = \frac{9\sigma^2\left(\nu+1\right)c}{\delta^2 2^{k-2}}\left(\frac{1}{2}\right) \tag{2}$$

From Equation 2, ν is the number of interaction degrees of freedom, c is the number of factor-level combinations for the factors that are involved in the interaction, *k* is the number of factors involved in the interaction, and δ is the minimum difference of interest among the interaction effects.

Based on Equation 1, the minimum sample size necessary for detecting a mean lateral placement difference of 6 inches before and after installation of the all-weather work zone pavement marking system at each site is

$$n_{lp} = \left(3r\sigma/\Delta\right)^2 = \left(3\times2\times20/6\right)^2 = 400$$

Based on Equation 2, the minimum sample size necessary for detecting a mean lateral placement difference of at least 6 inches in any two interaction means between pavement marking treatment and weather factor at each site is likewise

$$n_{lp} = \frac{9\sigma^2\left(\nu+1\right)c}{\delta^2 2^{k-2}}\left(\frac{1}{2}\right) = \frac{9\times20^2\left(1+1\right)\times4}{6^2 2^{2-2}}\left(\frac{1}{2}\right) = 400$$

The sample size of 400 is selected to assure the power of the tests to be at least 0.90 for the mean lateral placement difference. Thus, at each site the desired number of vehicles to be observed at night for each pavement marking treatment (control and experimental) and weather condition (dry and wet) combination is at least 100. As mentioned previously, data should also be collected for each pavement marking treatment during daytime dry pavement conditions. At each site, the desired number of vehicles for each daytime treatment condition is also 100. It should be noted that these numbers are the minimum number of usable data points. More data will need to be collected in the field to ensure that at least 100 usable data points are obtained for each condition.

The above calculations were used to identify the minimum sample size needed for identifying meaningful differences in the mean lateral placement among treatments. However, previous research (*1, 2*) has also reported that the variance of vehicle lateral placement is strongly correlated with crash crates. Therefore, assuming a control treatment standard deviation equal to 20 inches, Table 2 shows the maximum experimental treatment standard deviations for which a difference could be detected for various sample sizes and confidence levels. For example, with a sample size of 100 vehicles and a 95 percent confidence level, a significant difference between the treatments' variances would only be detected when the experimental treatment standard deviation is equal to or less than 16 inches. In other words, it would be possible to detect a 20 percent reduction in lateral placement standard deviation with that sample size. Reducing the confidence level and/or increasing the sample size both increase the maximum experimental standard deviation for which a significant difference from the control condition can be detected. If it were desirable to detect as little as a 10 percent reduction in the lateral placement standard deviation (i.e., from 20 inches down to 18 inches), it would be necessary to collect data from 250 vehicles to retain a level of significance of 0.05. If, however, one accepted a higher level of significance, such as 0.15, then it would only be necessary to collect data from 150 vehicles to conclude that the standard deviations are different.

Table 2. Maximum Experimental Treatment Standard Deviation that Would Yield a Significant Difference Between Treatment Variances [a]

Sample Size (vehicles)	Level of Significance (alpha) [b]			
	0.05	**0.1**	**0.15**	**0.2**
100	16	17	17	18
150	16	17	18	18
200	17	18	18	18
250	18	18	18	18
300	18	18	18	19

[a] The standard deviation is the square root of the variance. Based on a two-tailed F distribution. Assumes a control treatment standard deviation of 20 inches (variance of 400 inches^2).
[b] The significance level is 1-alpha (e.g., alpha of 0.05 is a 95 percent confidence level).

Based on Table 2, TTI recommends a minimum sample size of 200 vehicles for each pavement marking treatment (control and experimental) and weather condition (dry and wet) combination; totaling 800 vehicles per site. This sample size will allow researchers to confidently identify differences in both the mean lateral placement and variance of vehicle lateral placement among treatments, without placing undue burden on the data collection effort (especially since all sites should be on high-volume roadways).

DATA REDUCTION AND ANALYSIS

At a minimum, the following measures of effectiveness (MOEs) should be utilized to determine the effectiveness of the all-weather work zone pavement marking system at night under wet-weather conditions:

- mean lateral placement of vehicle in the travel lane,
- variance in the lateral placement, and
- rate of inadvertent contact with edge line markings.

Comparison of the mean vehicle lateral placement data will allow researchers to determine if there are differences among the treatments in how drivers position their vehicles in the outside travel lane. It is believed that vehicle paths located near the center of the travel lane may result in higher levels of safety (*8*). Thus, the amount of deviation from the center of the travel lane provides an indication of crash potential.

As mentioned above, previous research has also shown a correlation between the variance of vehicle lateral placement and crash frequency. It is hypothesized that the installation of treatments that reduce the variance of lateral placement (indicating more uniform driving performance) will lead to a lower crash frequency.

The rate of inadvertent contact with the edge line marking is similar to lateral placement in that it indicates the potential of a crash resulting from inappropriate lateral position. Thus, a reduction in this rate would be considered a positive safety benefit.

Mean speed and variance at the upstream data collection location should be compared amongst pavement marking treatments at each site and across sites to determine if the traffic characteristics are similar or may have been affected by uncontrollable extraneous variables. Lateral placement and speed data collected under dry pavement conditions (both at night and during the day) should also be used to help identify any unrelated conditions that might have affected the nighttime, wet-weather data. In addition, these data may reveal additional benefits to using the all-weather work zone pavement marking system under dry pavement conditions (night or day) or during daytime wet-weather conditions.

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