EVALUATION OF SOLAR-POWERED RAISED PAVEMENT MARKERS

Final Report

SPR 304-441

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16. Abstract

An evaluation of a limited number of solar-powered raised pavement markers (SRPMs) was conducted to determine if this type of marker would be more visible than retroreflective markers in some situations on Oregon highways. SRPMs typically use Light Emitting Diodes (LEDs) that are powered by solar cells. Some markers have retroreflective surfaces as well. The Oregon Department of Transportation, Research Unit, performed preliminary tests which included environmental tests (extreme temperatures, immersion), optical performance tests, and observation tests. Selected markers were sent to the Federal Highway Administration's Photometric and Visibility Laboratory (PVL) at the Turner-Fairbank Highway Research Center in McLean, Virginia for additional evaluation. A series of tests was performed to measure both the LED signal and the retroreflected light. It was found that each type of marker had significant shortcomings, so the project was terminated prior to field trials being performed.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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EVALUATION OF SOLAR-POWERED RAISED PAVEMENT MARKERS

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1.0 INTRODUCTION

1.1 BACKGROUND

This study was initiated in 2004 when the Oregon Department of Transportation (ODOT) was introduced to solar-powered raised pavement markers (SRPMs) by a vendor. A demonstration project was funded to look into the applicability of solar markers to Oregon and to determine if solar markers would be more visible than retroreflective markers in some situations and could perform effectively in all seasons. SRPMs were installed in two locations and performed satisfactorily.[1] However, after ODOT became aware of the range of markers available and the potential issues related to poor performance, it was decided in October 2006 that a more comprehensive study was needed. This study included laboratory testing and field observations. The tests performed were appropriate for their proposed use, which was limited to raised medians or other placements where the markers are not generally exposed directly to traffic. The objective of the study was to determine what types of markers would operate most effectively under the climatic and roadway conditions in Oregon in situations where retroreflective raised pavement markers (RRPMs) do not operate properly.

1.2 RAISED PAVEMENT MARKERS IN USE IN OREGON

Raised pavement markers (RPMs) have been in use in Oregon for many years. In the mid-1980's the ODOT Construction Section, through its Qualified Products Program, set up laboratory and field tests to determine which markers could be placed on state highways. Subsequently Standard Guidelines for Product Review (Appendix A) were developed, which were based on federal testing standards in effect at the time. ODOT's guidelines are currently being revised to be consistent with current specifications developed by ASTM and used by Federal Highway Administration (FHWA). The American Society for Testing and Materials (ASTM) standard specifications (D4280) were used as the basis for the testing completed for this research project.

Standard drawings TM502, TM515, TM517 (Appendix B) provide guidance for proper layout and installation of RRPMs. The use of RPMs on state highways is currently determined on a case-by-case basis by the Region Traffic Engineer in consultation with the District Manager. ODOT is in the process of developing guidance for RPM use and region-wide RPM plans to ensure consistency, especially for highway routes that cross region borders.

While essentially effective, retroreflective RPM's have some limitations. When utilized in situations where the road curvature and terrain is such that headlights of approaching cars do not

[1] The two locations were in southern Oregon. One site was on the narrow median of a two-lane bridge where there had been a history of crashes. The second location was on a raised median installed to replace a two way left-turn lane. Both road sections were relatively straight and with good sight distance.

shine directly on the marker, they are not effective. Fog and heavy rain also impact performance. Additionally the retroreflective qualities tend to degrade quickly.

1.3 SOLAR-POWERED RAISED PAVEMENT MARKERS

In response to the limitations of RRPMs, manufacturers began investigating alternative devices that would be more effective under certain conditions. Solar-powered lights offer some advantages as has been demonstrated in products developed for airport lighting and marine situations. The products typically use Light Emitting Diodes (LEDs) that are powered by solar cells. Solar cells convert sunlight directly into electricity. Solar markers use either a battery to store the charge that powers the LED or a capacitor. Markers are available from many different manufacturers and can be ordered as one-sided or two-sided and in different colors.

In addition to one or more LEDs, some markers are designed with a retroreflective surface so that they essentially provide two different types of illumination, depending on the conditions. Whether a marker had a retroreflective surface or not was initially considered insignificant in this study, since the purpose of the research was to determine if solar-powered markers were effective and could be used in situations not suitable for RRPMs. When testing determined limited light output from the LEDs, however, the lack of an effective retroreflective surface became a disqualifying characteristic.

Some markers are designed with a stud that is embedded in the pavement. Most can be installed either with a metal fastener similar to a screw or epoxy. The design varies considerably depending on the manufacturer and model. Figure 1.1 displays some of the markers that were included in this study.

Figure 1.1: Selection of solar raised pavement markers in testing lab

In the mid-1990's, when LED technology was new, British Columbia established requirements for solar powered markers to be installed on median barriers. The marker that was selected was chosen because it had a wide viewing angle, could be guaranteed for two years, and was maintainable. While not entirely successful, this experience led to additional installations of markers in British Columbia and helped to encourage the development of this technology so that markers available today are more reliable and more durable. In the last decade, many manufacturers have developed products and made them available world-wide in various colors and configurations.

For purposes of application on Oregon highways and for this study, the products being tested were limited to those that were white or amber and met the size specifications in place for RPMs. ODOT contacted all manufacturers that could be identified through an internet search and through referrals and requested white and amber products for testing. There were eight different models tested. Table 1.1 lists the models included in this study.

Table 1.1: Solar-powered raised pavement markers

Manufacturer	Supplier	Model
Astucia	Highway Safety Group	S-Series(IRS)
BeamCo Ltd	Illinois Solar Products	EL-806
ETL, Secure Logic	ETL, Secure Logic	26200
Fuzhou Richie Electric	Intelligent Traffic Equipment Marketing Ltd	RH-4300
ITEM	Intelligent Traffic Equipment Marketing Ltd	I-Marker 701
Miracle	SolarPath	Litemark T-1
Miracle	SolarPath	MS-200
Sherwin Industries	Sherwin Industries	LML

2.0 LITERATURE REVIEW

The literature review consisted of a review of published reports, a survey of states, and an investigation of the installation of SRPMs in other countries.

Literature regarding retroreflective raised pavement markers was reviewed for general background for this study. For the most part, the relevance of these studies to the development of the testing and performance criteria for solar-powered median markers is limited. Several studies on solar markers are summarized in this chapter, as they provide useful background information on the application of this technology and insight useful to the development of the testing protocol.

A National Cooperative Highway Research Program (NCHRP) synthesis project – Illuminated, Active, In-Pavement Marker Systems – which was initiated in December 2006 and should be completed in FY2008, may provide advancement to the state of knowledge about solar-powered pavement markers. The report that will be published at the completion of the project should be consulted for additional information on solar markers as well as other internally illuminated markers.

2.1 PUBLISHED REPORTS

2.1.1 Use of raised pavement markers

The Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) provides general guidance on raised pavement markers and requirements for their design, use, and placement. The MUTCD differentiates between non-retroreflective, retroreflective, and internally illuminated raised pavement markers (*FHWA 2003*).

The MUTCD sets a standard as follows: "A raised pavement marker shall be a device with a height of at least 10 mm (0.4 in) mounted on or in a road surface that is intended to be used as a positioning guide or to supplement or substitute for pavement markings or to mark the position of a fire hydrant. The color of raised pavement markers under both daylight and nighttime conditions shall conform to the color of the marking for which they serve as a positioning guide, or for which they supplement or substitute." (Section 3B.11)

The supporting information suggests that retroreflective and internally illuminated raised pavement markers can be used interchangeably and that non-retroreflective markings have more limitations. The guidelines state: "Retroreflective or internally illuminated raised pavement markers, or non-retroreflective raised pavement markers supplemented by retroreflective or internally illuminated markers may be substituted for markings of other types." (Section 3B.14)

Section 3B.21 of the MUTCD addresses curb markings: "Curb markings are most often used to indicate parking regulations or to delineate the curb." The guidance states: "Retroreflective solid yellow markings should be placed on the noses of raised medians and curbs of islands that are located in the line of traffic flow where the curb serves to channel traffic to the right of the obstruction."

Guidelines for the Use of Raised Pavement Markers (*Grant and Bloomfield 1995*) provide general delineation requirements based on research findings. These requirements include supplementing left edge lines with RPMs and centerlines as recommended per road geometry. Additional research is needed to provide more specific information on the use of RPMs and the minimum RPM reflectivity required for driver guidance. The following specific considerations are given:

- Drivers 65 and older may require four times as much light as 39-year-old drivers.
- Driver perception-reaction time increases with age.
- Two seconds of preview time is needed for short range guidance; and three seconds for long range guidance. At 25 mph delineation must be visible at 110 ft; at 55 mph delineation must be visible at least 250 ft.
- Poor visibility conditions (fog, rain, and glare) necessitate different lighting levels.

2.1.2 Measurement of retroreflectivity

The MUTCD does not establish minimum retroreflectivity levels, though Section 2A.09 is reserved for these standards based on FHWA rulemaking (*FHWA 2003*).

The Roadway Delineation Practices Handbook (*Migletz, et al. 1994*) supplements information in the MUTCD. A chapter is devoted to the characteristics and measurement of retroreflectivity. Minimum brightness requirements for RRPMs, based on research studies and experiences of various states, are presented in this publication . Since the Handbook was published, the standards have undergone additional review and have been revised by the American Society for Testing and Materials (*D4280 Standard Specifications for Extended Life Type, Nonplowable, Raised Retroreflective Pavement Markers* and *E809 Standard Practice for Measuring Photometric Characteristics of Retroreflectors*) (*ASTM 2002; ASTM 2004*). These ASTM specifications and testing practices are utilized now by the FHWA, Turner-Fairbank Photometric and Visibility Laboratory. The specifications ODOT used for testing are based on these standards.

Since direct measurement of brightness is not always reliable (*Migletz, et al. 1994*), many states have supplemented readings from retroreflectometers with subjective evaluations. Tests or subjective evaluations may be performed to consider contrast with the background, conspicuity, the distance of legibility and variations in readings between wet versus dry pavements. Some tests consider the greater needs of older drivers, who require brighter delineation.

Measurement of the intensity of the light given off by solar markers is not addressed in any of these documents.

2.1.3 Maintenance of raised pavement markers

The literature stresses the need for ongoing monitoring of performance. The Roadway Delineation Practices Handbook and other publications, such as Pavement Marking Materials and Markers: Real-World Relationship Between Retroreflectivity and Safety Over Time (*Bahar, et al. 2006*), provide insight into the rapid loss of retroreflectivity once markers are installed in pavement. Within a few months retroreflectivity can drop to as little as 1/50 of the initial level. This is primarily due to dirt and damage from vehicles.

While maintaining retroreflectivity is the primary maintenance issue, a marker becoming detached from the pavement is also a problem, especially on highways with high average daily traffic volumes (ADTs).

The NCHRP Synthesis 306, Long-Term Pavement Marking Practices (*Migletz and Graham 2002*) provides detailed information on practices in place in some states to replace markers:

- Texas DOT's guidelines suggest a yearly replacement schedule if over 50,000 ADT, every 2-3 years if between 10,000 and 50,000 ADT, and every 3-4 years for lower volumes roadways.
- Oregon uses a 2-year replacement estimated for its raised pavement markers.

2.1.4 Visibility of raised pavement markers

Two recent reports address how the installation of RPMs affects safety. One of these reports, Safety Evaluation of Permanent Raised Pavement Markers (*Bahar, et al. 2004*) provides information about the benefits of RPMs compared to standard pavement markings, noting that they were developed to provide delineation over a wide range of environmental conditions.

The visibility of RPMs depends on their placement, vehicle headlights, the highway geometry, and driver visual capabilities. They provide better visibility than painted markings but deteriorate more rapidly over time.

Road geometry affects delineator visibility. The more the face of the delineator is aligned perpendicular to the line of sight of the driver, the more visible the device will be. On curves minimum visibility will be obtained when the marker face is aligned perpendicular to the tangent of the curve.

Driver characteristics affect delineator visibility. As people age their contrast sensitivity deteriorates and preview distances decline. For this reason, many older drivers reduce their nighttime driving.

Pavement Marking Materials and Markers: Real-World Relationship Between Retroreflectivity and Safety Over Time (*Bahar, et al. 2006*) presents the results of research using California's data on RPM installations and crashes. This study found that while it is important for markers to be present and visible, the relative retroreflectivity is not as important. Drivers adapt to different levels of visibility by raising or lowering their speed.

2.1.5 Solar-powered raised pavement markers

Most of the literature does not include information on solar powered markers: their use, measurement of visibility, or maintenance. Long-Term Pavement Marking Practices (*Migletz and Graham 2002*) does acknowledge the potential for solar markers to extend the viewing distance to over 600 meters at night.

VicRoads installed self-activated pavement markers in several locations in Victoria in southeastern Australia and commissioned ARRB Transport Research to evaluate the results. The research was reported in Trial and Evaluation of Internally Illuminated Pavement Markers (*Styles, et al. 2004*). Markers sensitive to light, cold, and moisture were included in the test.

It was the premise that markers sensitive to light would have advantages over retroreflective markers which appear bright only when headlights are shining directly on them. These markers were designed to provide drivers with consistent light output over a range of angles. This gives them the advantage of offering the driver a clear indication of the road curvature. Laboratory tests were performed to determine the consistency of the markers' on-off thresholds in responding to fading light, fog, and low temperatures. In-service performance was assessed. The impact of the markers on driver behavior was also assessed. The evaluation showed that the markers switched off long before daylight, even on overcast days. Data kept by VicRoads indicated the markers were subject to traffic damage, theft, and vandalism. A study of driver behavior indicated that high beam headlight and brake use were not significantly affected, and there were some reductions in travel over the centerline and speed. The following conclusions were based on the evaluation:

- The tested markers responded well enough to environmental conditions for their purpose.
- The tested markers are not "sufficiently robust in service."

A study was performed in Japan to determine the required intensity of LED delineators under conditions with reduced visibility. The study was performed in the summer of 2004 in Hokkaido under foggy conditions. Three types of LED delineators were tested. Markers were evaluated in daytime and nighttime conditions by a group of 20 persons. The study concluded that "to make the delineator 'visible' from the observation distance of 200 m under foggy conditions luminous intensities of 1000 candelas and 70 candelas are desirable for daytime and nighttime, respectively" (*Hagiwara, et al. 2006*).

Astucia, one of the manufacturers of solar-powered markers contracted with TRL Limited to conduct research on driver behavior in response to active illuminated road studs (i.e., markers) versus standard retroreflective (passive) studs (*Reed 2006*). A driving simulator was used to create a 37.1 km length of rural road which was driven twice by each of the 36 participants, who represented a range of age groups. In one of the drives the road section had active studs and in one, passive studs. The simulator collected information about the way the vehicle was driven on each trial. The results indicated that drivers (particularly in right turns, and older drivers) maintained their control better when guided by active studs than passive studs. Drivers participating in the trial viewed the installation of the active studs positively.

2.2 SURVEY OF STATES

A survey was conducted in 2005 of all states to determine if any state DOT had had experience with using solar-powered raised pavement markers. Of the twenty states that responded, only Texas had used solar-powered markers. A more recent search revealed that Kansas has also used solar-powered RPMs. (See Appendix C for a summary of responses and a copy of the questionnaire that was sent.)

Solar-powered illuminated raised pavement markers were installed in a 12-mile section on I-135 in Kansas to delineate a southbound left-lane drop taper at the north end of the project and to provide additional guidance through the lane drop. Results of a study done as part of the Midwest Smart Work Zone Development Initiative showed that the markers did not have a significant impact. "Subjective evaluation and review of driver's view video footage suggested that the light emitted from the units was not sufficient to effectively improve taper delineation (*Meyer 2000*).

The City of Carefree, Arizona has installed solar-powered pavement markers on a section of their main street. There had been several crashes on this segment, including one fatal. The markers have been functioning well for over a year. According to the City, no new crashes have been recorded.

The NCHRP study described in Section 2.4 can be expected to provide an update on the status of their use in the U.S. Early findings indicate relatively wide use of solar-powered traffic devices for pedestrian crosswalks. Findings to date have not revealed any comprehensive evaluation of markers to be installed as intended in Oregon.

2.3 USE OF SOLAR-POWERED MARKERS IN OTHER COUNTRIES

Solar-powered pavement markers seem to be used more widely in other countries than in the United States.

2.3.1 Canada

Solar-powered markers were first installed in British Columbia in 1996 (*Froese 2006*). While these markers have been removed and have been replaced with other markings, the results of this first trial were positive enough that British Columbia has installed markers on other roadways. One of these locations is a 5 km stretch of Highway 7 outside of Mission, British Columbia. It was a recessed installation due to the use of snow plows (*ITEM 2006*).

Ontario Canada has also used solar markers. One such location is Highway 59 south of Norwich. Markers were placed at 12-meter intervals. It was found that the markers were able to maintain their visibility during poor driving conditions and that, since the snow melts faster on the marker than on road, damage from snow plowing could be avoided (*Institute of Transportation Engineers 1997*).

2.3.2 England

In 2005 the United Kingdom Department of Transport approved an Astucia solar-powered road stud for installation in the United Kingdom. The stud was trialed and it was found that the light source continued to perform satisfactorily for a 12-month period. The approval permits the product (colored white, red, yellow, or green) to be used on any public road in the United Kingdom.

This approval was after studs had been installed at a number of locations in the United Kingdom with a positive safety outcome. Field trial reports indicate the studs are visible up to ten times farther than retroreflective studs. (*Astucia 2005*)

2.3.3 South Africa

A provincial department of transport in South Africa is using solar-powered light studs embedded in pavement to prevent crashes. Markers are designed and installed so they show white to the driver traveling in the proper lane and red if the driver crosses over to the oncoming lane. The markers provide visibility up to a kilometer. Twenty thousand markers have been installed on Road 66 north of the city of Durban. (*Crawford 2005*).

According to the study there were 350 crashes (21 fatal and 71 serious) in the 12 months prior to the installation of the markers and 41 crashes (one fatal and one serious) in the same period after their installation.

2.3.4 Australia

VicRoads installed self-activated pavement markers in several locations in Victoria and commissioned ARRB Transport Research to evaluate the results. (*Styles, et al. 2004*). Tests included markers sensitive to light, cold and moisture. These markers were designed to provide drivers with consistent light output over a range of angles. Laboratory tests were performed to determine the markers' consistency in responding to fading light, fog, and low temperatures. In-service performance and the impact of the markers on driver behavior were assessed. The evaluation showed that the markers will switch off long before daylight, even on overcast days. Data kept by VicRoads indicated the markers were subject to traffic damage, theft, and vandalism.

2.4 NCHRP STUDY

NCHRP Project 20-5 includes a range of synthesis topics. One of these topics, 38-13 – Illuminated, Active, In-Pavement Marker Systems – will provide significant advancement to the state of knowledge about solar-powered pavement markers. The study was initiated in December 2006 and can be expected to be completed by in FY 2007-08. Information will be gathered by a literature review, a survey, and interviews about solar-powered markers and other illuminated, active pavement marking devices. The final scope of work identifies the following expectations for the research:

- Current practice;
- How does it work; does it work?
- How long has it been in use;
- Safety and operation analyses;
- Failures and flaws;
- Cost of implementation and maintenance;
- Day time vs. night time operation;
- Concrete vs. asphalt;
- Installation standards;
- When to use wired, wireless, solar;
- Cold weather/snow experience; extreme hot weather;
- LED replacement issues;
- Pavement resurfacing issues;
- How is the device activated?
- Impact of improper activation;
- Unintended consequences and benefits; e.g. over-driving or respecting crosswalks;
- Human factors information.

3.0 LABORATORY TESTS

The testing procedures for this study included laboratory tests, observation tests, a weathering test, and field tests. Initial laboratory tests, which included environmental and optical performance tests (luminous intensity and chromaticity), were performed by the ODOT Research Unit with assistance from the state traffic signal engineer. Federal Highway Administration's Photometric and Visibility Laboratory at the Turner-Fairbank Highway Research Center conducted additional tests to measure the LED signal and retroreflectivity of markers at different distances and angles designed to replicate what drivers would see on the road.

3.1 DEVELOPMENT OF LABORATORY TESTING PROTOCOL

Through the literature review and additional contacts with the Federal Highway Administration (FHWA) it was found that no procedures for testing solar markers had been established. The testing protocol that was used was developed by reviewing testing protocol in use at ODOT for other traffic control devices. Specific tests incorporated in the testing protocol were designed with consideration to specifications and testing procedures for raised pavement markers, traffic signal controllers, traffic signal LED display heads, and portable variable message signs.

ODOT staff drafted testing protocol to determine the effect of high and low temperatures, immersion in water for an extended time period, and optical performance. ODOT staff performed pilot laboratory tests on several of the solar-powered markers to be tested. As a result of these pilot tests, the testing protocol was refined. The tests performed in this research could be easily duplicated in the future, if necessary.

For example, it was initially thought that the best way to test the performance of markers under humid conditions was to expose them to the climatic conditions available in ODOT's concrete cure room. The humidity of the cure room is maintained at 100% while the temperature is maintained at 70º F. It was later determined that immersion of the markers in water for 24 hours was an adequate test of performance under high humidity.

Likewise the initial test used to measure the optical performance of markers was revised after the initial test produced no useful results. A sample of markers was tested at the ODOT Materials Laboratory using a test (ASTM T 257-96) used for retroreflective markers. The test uses a projected standard light source which is reflected back to a photoreceptor. The observation angle is controlled by a goniometer. None of the samples tested met the minimum standards for pavement markers. It was determined that only the output of the LEDs could be tested. The procedure used for testing LED traffic signals was adapted for this purpose and supplemented with an observation test. (Tests done later at Turner-Fairbank Photometric and Visibility Laboratory were designed to measure both the LED signal and the retroreflectivity of markers.)

The testing protocol used in tests performed by ODOT is outlined in Table 3.1. Appendix D summarizes the testing protocol and the results.

Table 3.1: ODOT laboratory testing protocol

1.0 Manufacturer's Specifications and Confirmation

Test Description: Record information from manufacturer and confirm by actual measurement.

- Length (inches)
- Width (inches)
- Height (inches)
- Color of display
- Number of LEDs
- Storage device
- Operating temperature range (°C)
- Luminance level (mcd)
- Visibility range (feet)

Two of each product, randomly labeled by Product Number and Group "A" or "B", are to be tested.

2.0 Environmental Tests

- **Extreme temperatures**
  Test Description: Raise or lower temperature (at a rate not more than 16 ° per hour) in TSSU Environmental Testing Chamber to extreme limits and maintain for 12 hours. Record date and time. Observe performance at extremes.
  Low temperature (-34° C); High temperature (73° C)
- **Immersion Test**
  Test description: Put markers in water for 24 hours and observe that no apparent moisture intrusion has occurred.
- **Post-Test Evaluation**
  Fully charge all markers, place in dark. Check visibility after 12, 16, and 20 hours. It is desirable that display is still visible after 16 hours.

3.0 Optical Performance (LEDs only; not retroreflective surface)

- **Test 1 Description**:
  Determine test time. At least 24 hours before the test expose one of each product to incandescent light for at least 8 hours. Remove and place where LED will stay on for 16 hours. Call this Group B.
  Expose one of each product to incandescent light for at least 8 hours immediately prior to the time of the test. Call this Group A.
  Conduct test on Group A markers as follows: Using the Photo Research PR 650 Spectroradiometer/Colorimeter take 3 readings of luminous intensity and record highest and take three x and y coordinate readings, and record the average. Repeat for Group B markers. Determine if marker meets ASTM 4280 color standards.
- **Test 2.1 Description**:
  Follow above procedure to expose Group A and B products. Set products in field so they are viewed from 200 meters at an angle of 0° twice in different order. Have observers give subjective evaluation of visibility on a scale of 1-5 with 5=excellent visibility, 4=good visibility, 3=fair visibility, 2=visible but not recommended for installation, 1=not visible.

  Average score for all observers for Group A markers should be 3.0 or above.

  Average score for all observers for Group B markers should be 2.5 or above.
- **Test 2.2 Description:**
  Position groups of 3-4 markers from Group A at an angle of 20° and have observers indicate the distance at which light is visible and rate the visibility as above.
  Average score for all observers should be 2.0 or above with no more than 25% of the observations from less than 150 meters.

  Average score for observation tests

4.0 Evaluate results of tests and identify products for further testing

3.2 PERFORMANCE OF LABORATORY TESTING

Two markers of each model type were put through the laboratory tests. They were randomly assigned to one of two groups, referred to throughout the study as Group A and Group B. Group A markers were used to test performance immediately after being charged for a period of at least 12 hours; Group B markers were used to test performance after being charged for a period of at least 12 hours and after discharging for at least 14 hours. This time period was used to approximate the length of the longest period of darkness in Oregon.

3.2.1 Environmental tests

3.2.1.1 Extreme temperature test

The test used to determine tolerance for extreme temperatures was identical to that used for traffic controllers. Two groups of 14 markers were charged for 16 hours by placing them under incandescent light. The researchers had previously determined that incandescent light would be a reliable substitute for solar light and would allow more flexibility in scheduling each of the tests.

All 28 markers were placed in the testing chamber at ODOT's Traffic Signal Services Unit. Starting at the temperature of 15º C, the chamber temperature was gradually dropped to -34° C so that temperature reduction did not exceed more than 16º C per hour. Observations were made when the extreme low temperature was reached. At that time two units were not working and four were very dim. It is not known if this was caused by the cold temperature or the length of the discharge time.

After holding this temperature for 12 hours, the temperature was gradually raised to 73° C. Observations were made when the extreme high temperature was reached. Twelve of the markers had extinguished. Since they had been discharging for 31 hours, it was most likely the long discharge time rather then the heat that caused them to go dark, though this could not be ascertained.

Marker 7B had shut off at less then an hour into the cold cycle but started shining again during the hot cycle at about 66° C. Marker 7A continued to shine very brightly. During the cold cycle Marker 8B did not consistently maintain its visibility. It alternated between not shining at all and having good visibility, then going entirely dark by the end of the test.

Later this test was repeated for two additional sets of markers which, unlike the markers in the initial test, flashed on and off instead of staying continuously illuminated. The results are incorporated with the results from the earlier test.

3.2.1.2 Immersion test

All 32 markers were placed in a tub of water so that each one was fully immersed. See Figure 3.1. After 24 hours, all markers were removed and allowed to dry. Table 3.2 records observations made to determine if there was visible seepage or condensation.

Figure 3.1: Immersion test set up in testing lab

Table 3.2: Observations after 24-hour submersion test

Marker Number	Group	Notes*	Group	Notes*
1	A		B	
2	A		B	
3	A		B	
4	A	LED cloudy	B	Water dripping
5	A	LEDs cloudy	B	LEDs cloudy
6	A	Water in case	B	Water in case; small crack
7	A		B	
8	A		B	Water in case
9	A	Condensation in LED lens	B	Condensation in LED lens
10	A		B	
11	A		B	
12	A		B	
13	A		B	
14	A		B	
15	A		B	
16	A		B	Condensation in LED lens

*The "Notes" column is blank if there was no visible water or condensation.

3.2.1.3 Post-environmental test evaluation

All 32 markers were charged for 12 hours and then placed in the dark to determine how long they would maintain their visibility. The markers were checked after 12, 16, and 20 hours. It had previously been determined that the markers should hold their charge for at least 16 hours, which would equate to slightly more than the longest night in mid-winter in Oregon. Observations were made and are recorded in Figure 3.2.

Eight of the units did not remain on or were very dim after 12 hours. The remaining 24 were well lit after 16 hours, and most were still lit at the end of 20 hours. The yellow flashing units continued to flash at the 20-hour mark, while the white flashing units went dark after 16 hours.

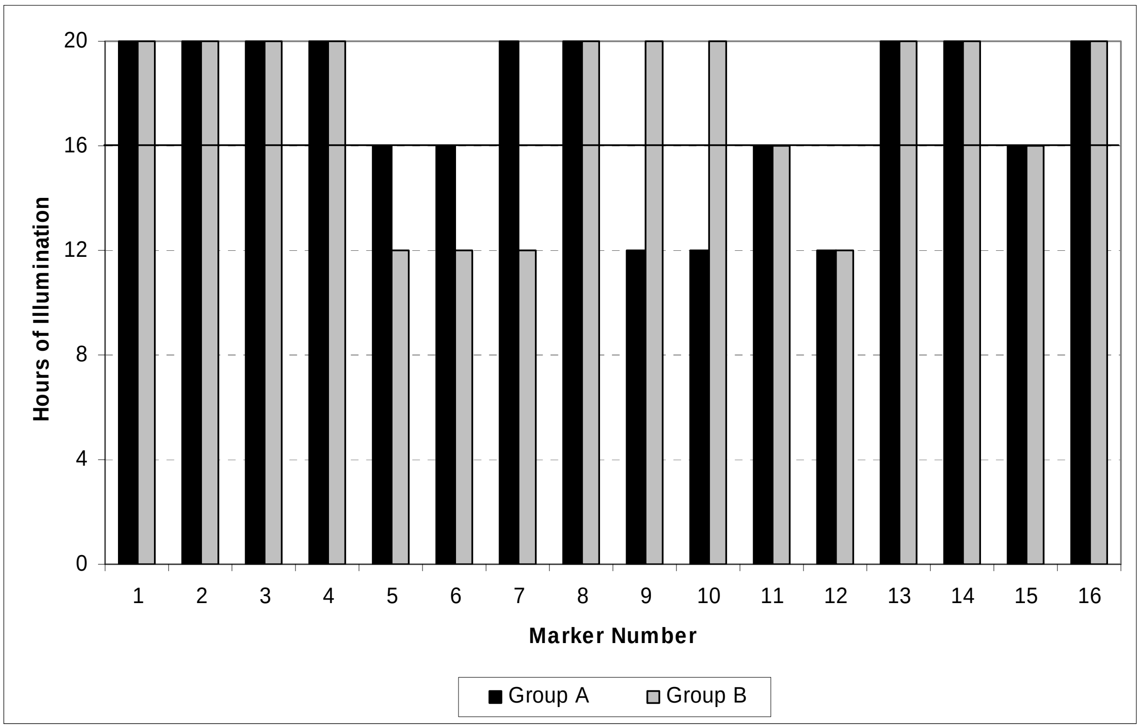


Figure 3.2: Hours SRPMs were illuminated before being too dim to be useful

3.2.2 Optical performance tests

All markers were determined to have performed well enough in the environmental tests to be included in the optical performance tests. Due to the limited number of markers of each type tested, it was deemed appropriate to note performance in the environmental test but not to use the results to eliminate markers from further testing.

3.2.2.1 *Spectroradiometer test*

The following equipment was needed for this test:

- Spectroradiometer[2] placed on a tripod.
- Lapsphere Spectralon, a 142mm (5") square "white tile" that sits on a tripod and serves as a target for the light to be measured. It is 99+% diffuse reflectance material.
- A platform on which to place the solar-powered marker.

Figure 3.3 shows the set up for the photometric equipment.

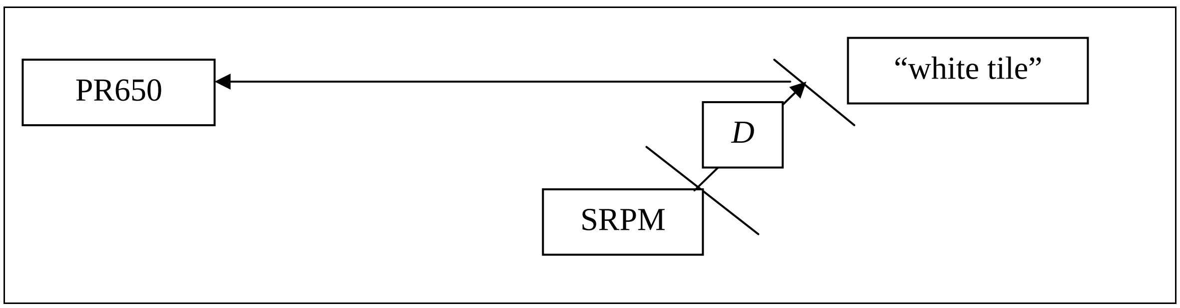


Figure 3.3: Photometric equipment setup

The PR650 measures the energy from all wave lengths of visible light and gives a reading of total luminous intensity in candelas per square meter (cd/m^2). The number of candelas then is calculated using Equation 3-1:

$$cd = (cd/m^2) * D^2 * 3.14 \qquad \textbf{(3-1)}$$

where:
cd = luminous intensity in candelas
D= the distance from the test sample to the white screen in meters

The PR650 also provides chromaticity. The direct reading for x- and y-coordinates can then be looked up on the 1931 CIE (Commission International de L'Eclairage) Diagram (Figure 3.4) which is incorporated in the ASTM 4280 standards for raised retroreflective pavement markers. A determination is made as to whether the color of the marker is acceptable.

Through a trial and error effort, the testing protocol was revised to require that the optical performance test be completed immediately after markers had been exposed to light for 12 hours and repeated after markers had discharged for at least 14 hours. It was

[2] Model PR-650 manufactured by Photo Research, Chatsworth, California

determined that the measurement be taken at .76 meters (30 inches) in order to maintain the reliability of the readings. Greater than this distance, readings could not be obtained; and lower distances were considered unreliable.

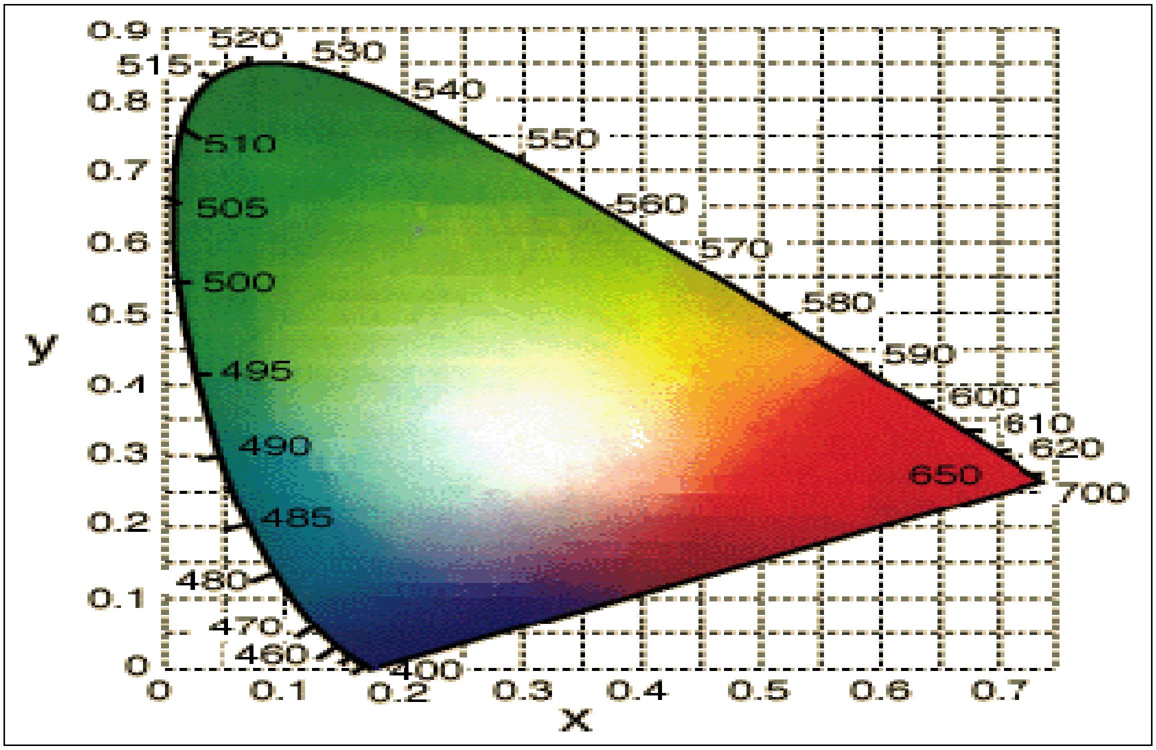


Figure 3.4: 1931 CIE diagram

The spectroradiometer test was performed using the procedure detailed in the testing protocol. At least three readings were taken on each marker; the highest reading was recorded. This was because the angle that the marker was set could not be specifically determined, so adjustments were made by one of the researchers based on a subjective evaluation. If a reading could not be taken at 30 inches (76 cm) no recording was made, as it was determined that readings taken at closer range would not be reliable. Readings taken on the markers with a flashing LED were considered unreliable and also are not recorded.

For this test, Group A markers were charged for 12 hours under incandescent light and tested immediately after being removed from the light. Markers in Group B were also charged for 12 hours under incandescent light but allowed to discharge for 16 hours prior to testing. The readings taken were used to calculate the luminous intensity in candelas. The results of this calculation are given in Table 3.3. Since these readings were based on limited testing and less than ideal testing circumstances, they were not used to accept or reject any marker but to help identify markers for additional testing by FHWA.

Table 3.3: Luminous intensity in candelas

Marker No.	Group A	Group B
1	low	low
2	low	low
3	1.02	0.91
4	low	low
5	3.41	1.57
6	4.45	0.40
7	2.61	low
8	0.71	1.42
9	low	0.38
10	0.53	low
11	low	low
12	1.20	low
13	low	low
14	0.44	0.36
15	Test not valid for flashing LED.	
16		

The spectroradiometer also provides a reading of chromaticity. The direct reading for x- and y-coordinates can then be looked up on the 1931 CIE (Commission International de L'Eclairage) Diagram, to determine if the reading falls within the range for that color. As mentioned above, these standards are incorporated in the ASTM 4280 standards for raised retroreflective pavement markers. Table 3.4 shows the chromatic readings for the markers being tested. About half of the markers met the ASTM standards; six did not; and some could not be tested due to low light.

Table 3.4: Chromatic readings for markers in study

Marker	Color	Chromaticity X	Chromaticity Y	Meets ASTM 4280
1	white	0.309	0.329	yes
2	yellow	n/a	n/a	n/a
3	white	0.270	0.272	no
4	yellow	0.550	0.435	yes
5	white	0.276	0.270	no
6	yellow	0.586	0.413	yes
7	white	0.270	0.275	no
8	yellow	0.563	0.430	yes
9	yellow	0.567	0.415	yes
10	yellow	0.569	0.414	yes
11	white	0.299	0.316	no
12	yellow	0.550	0.441	no
13	white	0.309	0.297	yes
14	yellow	0.542	0.436	no
15	white	0.312	0.316	yes
16	yellow	0.562	0.421	yes

Chromaticity readings were taken for both Group A and B markers. The reading most closely approximating the ASTM standard is given.

3.2.2.2 Observation test

The spectroradiometer test was followed by an observation test to gain a sense of what driver perception might be to the markers when they are placed on a raised median or other installation on an Oregon highway. There was no intention that the tests performed be comprehensive or that they should objectively assess driver response to the solar-powered markers if they were installed on a highway.

Observation tests were conducted at ODOT's District 3 Maintenance Yard. Five members of the Technical Advisory Committee for this project and four other ODOT staff viewed markers that were set up by ODOT Research Unit staff. Communication between the staff displaying the markers and observers was established by cell phone. Observations began after dark and took approximately an hour.

There was some background lighting from security lights on the buildings and in the yard which simulated actual installations where background light would also exist. The viewing station had been set up earlier in the day. Cones were set in a straight line every 82 feet (25 meters) from the area where the markers were set to the area where the observers stood. A sign displaying the distance from the marker display location was attached to each cone. Observers were stationed at 656 feet (200 meters) from the markers on a line at right angles to the cone line. Markers were set on a board 165 mm (6.5 inches) high, which was designed to emulate the height of a raised median where the markers might be installed on the highway.

The distance of 656 feet (200 meters) was chosen to represent driver perception reaction time under road conditions when visibility is limited. Studies have indicated that roadway delineation (pavement markings, RPMs included) should provide the motorist with three to five seconds or more preview time of the roadway alignment to allow for efficient, anticipatory steering behavior. At higher speeds and on approaches to sharp curves, a greater the preview distance is required to perceive and react appropriately. For a roadway with a posted speed of 65 mph, visible delineation for 475+ feet (145+ meters) (for 5 seconds of preview time) is desirable. The 656 feet (200 meters) used for testing was conservative, but not excessive, as it would provide a good preview distance of approximately seven seconds at 65 mph.

Figure 3.5 is a daytime photo of the site where the observation test took place. It shows the board where the markers were set for viewing. The observers stood at the far end of the line of cones.

Figure 3.5: Site for observation test

Markers were displayed at 0° individually in two different sequences, with Group A markers displayed first in each sequence. Each observer was asked to score the quality of the visibility of each marker using the following rating system: 5=excellent visibility, 4=good visibility, 3=fair visibility, 2=visible but not recommended for installation, 1=not visible. See Appendix E for a copy of the form used to score this test.

Following this test, a test in which markers were placed at a 20° angle was completed. Markers were viewed in groups of three or four with all markers in a group the same color. Only Group A markers were used for this test. In this test, observers who could not see a marker from 200 meters were allowed to come forward until the marker could be viewed. The observers noted both the distance at which the marker could be seen and the quality of the observation using the same rating scale as above. See Figure 3.6 for a photo of the marker placement for the 20° angle test.

Figure 3.6: Marker placement for 20° angle test

The scoring sheets for the nine observers were compiled. The average scores are shown in Table 3.5. If a marker could not be viewed at a 20° from 200 meters by seven of the nine participants, this is noted in the table. The table also shows whether the marker met the criteria established in the testing protocol. The testing protocol required that fully charged markers (Group A) should receive an average score of 3.00 which equates to "fair visibility" and that markers that have been discharging for 16 hours or more (Group B) should receive an average score of 2.50 or better. The testing protocol also required that markers can be seen at a 20° angle, ideally from a distance of 200 meters.

The results of the observation test in Table 3.5 shows the markers listed in descending order by average score. The markers that met all criteria are noted.

Table 3.5: Observation test results

Marker No.	Group A	3.00 or better	Group B	2.50 or better	20° Angle	Less than 150 meters*	2.00 or better at 150 m	Meets all Criteria	Average Score
15	4.61	X	4.44	X	3.13		X	X	4.06
16	4.06	X	4.17	X	2.56		X	X	3.59
5	4.44	X	3.83	X	2.33		X	X	3.54
6	4.44	X	2.94	X	2.11		X	X	3.17
3	2.94	X	2.72	X	2.33		X	X	2.67
7	3.83	X	1		3		X		2.61
10	3.06	X	2.28		2.44		X		2.59
1	2.67		2.61	X	2.22		X		2.50
8	2.89		1.83		2.44		X		2.39
13	2.56		2.72	X	1.88				2.38
14	2.94		2.67	X	1.44	#			2.35
2	2.44		2.11		1.67	#			2.07
12	2.78		1.06		2.22				2.02
4	2.17		2.28		1.56	#			2.00
11	2.67		1.28		1.75	#			1.90
9	1		2.44		1	#			1.48

*more than 2 observations taken at less than 150 meters

3.3 TEST RESULTS

Table 3.6 summarizes both the optical performance of the LEDs and environmental test results of the SRPMs. It was determined that the results were non-conclusive but that they seemed positive enough to merit additional evaluation.

Staff at FHWA's Photometric and Visibility Laboratory (PVL) at the Turner-Fairbank Highway Research Center (TFHRC) agreed to perform additional tests on some of the markers. The testing equipment and expertise offered significant advantages to ODOT's testing situation. Markers selected for additional testing had performed well in observation tests and represented the range of designs. The objective was not to determine what specific models performed the best but if the markers generally performed well enough to be placed on the highway. Chapter 4 details the methods used and results received from FHWA.

Table 3.6: Summary of laboratory test results for solar-powered raised pavement markers

	Environmental Test Results		Optical Performance Test Results						
			Spectroradiometer		Observation Results				
Marker No.	Extreme temperature/immersion test results	Hours illuminated*	Luminous intensity in candelas	Meets ASTM color standard	Group A	Group B	20° Angle	Average	Met all criteria for observation test
1		20/20	low reading	yes	2.67	2.61	2.22	2.50	
2		20/20		n/a	2.44	2.11	1.67	2.07	
3		20/20	1.02	no	2.94	2.72	2.33	2.67	x
4	LED cloudy; water dripping	20/20		yes	2.17	2.28	1.56	2.00	
5	LEDs cloudy	16/12	3.41	no	4.44	3.83	2.33	3.54	x
6	Water in case	16/12	4.45	yes	4.44	2.94	2.11	3.17	x
7	Stopped operating in cold cycle	20/12	2.61	no	3.83	1.00	3.00	2.61	
8	Did not maintain visibility consistently in cold cycle; water in case	20/20	1.42	yes	2.89	1.83	2.44	2.39	
9	Condensation in LED lens	12/20		yes	1.00	2.44	1.00	1.48	
10	Dim in cold cycle	12/20	0.53	yes	3.06	2.28	2.44	2.59	x
11	Dim in cold cycle	16/16		no	2.67	1.28	1.75	1.90	
12	Dim in cold cycle	12/12	1.2	no	2.78	1.06	2.22	2.02	
13		20/20	low	yes	2.56	2.72	1.88	2.38	
14		20/20	0.44	no	2.94	2.67	1.44	2.35	
15		16/16	reading unreliable	yes	4.61	4.44	3.13	4.06	x
16	Condensation in LED lens	20/20	reading unreliable	yes	4.06	4.17	2.56	3.59	x

*20 hour test. Results are shown for both Group A and B markers.

4.0 FEDERAL HIGHWAY ADMINISTRATION TESTING

In May 2007, ODOT sent five different models of solar-powered raised retroreflective pavement markers (SRPM) to FHWA for additional testing. These models had performed well in observation tests and adequately in laboratory tests. For each model, three white and three yellow markers were tested in FHWA's Photometric and Visibility Laboratory (PVL) at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, VA. Thus a total of 30 markers were used in the testing.

4.1 TESTING PROCEDURES

Table 4.1 lists the markers tested by FHWA, the types of measurements taken, and unique design features that affected testing. Due to the unique design features of the different models tested, the measurement techniques were slightly different. One brand of SRPMs had studs which extended down from the bottom surface of the SRPM. Thus, since the PVL goniometer uses a flat table to mount SRPMs for measurement, six of the 30 samples (Markers #3 and 4) could not be measured.

Table 4.1: Solar-powered raised pavement markers sent to FHWA for testing

Marker Number	Color	CIE Tests		ASTM Tests	Unique Design Feature
		Centerline	Edgeline		
3	White	No	No	No	Stud-mounted (plowable)
4	Yellow	No	No	No	Stud-mounted (plowable)
5	White	Yes	Yes	Yes	
6	Yellow	Yes	Yes	Yes	
10	White	Yes	No	No	3 LEDs; no retroreflective material
10	Yellow	Yes	No	No	3 LEDs; no retroreflective material
13	White	Yes	Yes	Yes	
14	Yellow	Yes	Yes	Yes	
15	White	Yes	No	Yes	Flashing LED; manual measurements required
16	Yellow	Yes	No	Yes	Flashing LED; manual measurements required

Prior to making measurements, all of the samples were placed outdoors in direct sunlight to completely charge the batteries. The 24 samples that were measured were placed on the goniometer table at 0-degrees (β_1, β_2, ε) and secured with electrical tape. All measurements were made in near total darkness with the exception of the projected light source.

The solar-powered LED SRPMs were measured on the PVL's computerized photometric range system. The system's three main components include a photopic-corrected silicon photoreceptor, an illuminant-A projection light source, and a 3-axis goniometer. The photoreceptor and light source are mounted on the "observation angle positioner" (OAP), which aligns the light source with the intersection of the three axes of the goniometer table, and permits the photoreceptor to be moved along a line that is orthogonal to the optical axis. A full description of the system may be found at http://www.roadvista.com/products/model940d.shtml.

Prior to data collection, a calibration was conducted on the photometric range system to ensure the device was properly aligned and calibrated. The calibration procedure required the goniometer table to first be aligned along the optical axis of the light source. Following alignment, the photoreceptor was placed on the goniometer table and a relative measurement of the illuminance provided by the light source was recorded. A second, absolute value of the illuminance provided by the light source was obtained using a calibrated LMT I-1000 illuminance meter.

The photoreceptor was then moved back to the OAP and used to measure the signal provided by the retroreflected and emitted light from the LED SRPMs. A second measurement was made with the light source blocked in order to obtain the signal provided by the LEDs alone. This value was subtracted from the signal provided by the retroreflected and emitted light to permit calculation of the coefficient of luminous intensity (R_I) of the retroreflecting element. R_I is the relative measurement of retroreflected illuminance provided by the LED SRPM times the square of the distance between the SRPM and the photoreceptor divided by the relative illuminance provided by the light source at the face of the LED SRPM. The units of R_I are candela per lux (cd/lux). The signal provided by the emitted light from the LED SRPMs is multiplied by the measured illuminance provided by the photometric range light source to obtain the luminous intensity (candela – cd) provided by the LEDs for each individual measurement geometry.

Following the calibration procedure background measurements were taken to establish a single baseline to which all the samples were compared.

4.1.1 Procedure A

In the first procedure, referred to as Procedure A, the CIE goniometric system of angles was used to measure the R_I values of SRPMs placed at various distances from the vehicle on the edge line and center line (*CIE 2001*). Table 4.2 gives the CIE geometries.

Table 4.2: CIE goniometric system of angles

Road Distance (meters)	Vehicle Headlight	Right Edgeline RRPM				Road Distance (meters)	Vehicle Headlight	Centerline RRPM			
		α	β1	β2	ε			α	β1	β2	ε
50	Left	0.66	0.60	2.61	28.95	50	Left	0.60	-1.10	-1.17	15.97
50	Right	1.01	-1.60	0.22	-55.04	50	Right	1.14	1.85	-1.94	-59.50
100	Left	0.33	0.20	1.33	24.52	100	Left	0.32	-0.57	-0.57	18.05
100	Right	0.53	-0.80	0.11	-55.27	100	Right	0.56	0.89	-1.00	-57.56
200	Left	0.17	0.07	0.67	22.26	200	Left	0.16	-0.29	-0.28	19.03
200	Right	0.27	-0.40	0.05	-55.38	200	Right	0.28	0.44	-0.51	-56.54
300	Left	0.11	0.04	0.44	21.50	300	Left	0.11	-0.19	-0.18	19.35
300	Right	0.18	-0.27	0.03	-55.42	300	Right	0.19	0.29	-0.34	-56.19

CIE center line measurements were taken for all samples except for the stud-mounted SRPMs. The SRPMs that had both LEDs and retroreflective materials on the same side were measured using two different techniques. Measurements of the retroreflective material and LEDs were made using both the projected light source and photoreceptor. The measurements were then repeated with the light source turned off to determine the LED contribution to the signal.

A slightly different technique was used for measuring the SRPMs that had flashing LEDs (Markers #15 and 16). Due to the short "on-time" of the flashing LEDs (less than 0.5 sec), measurements had to be taken manually to try to capture the peak output of the LEDs. Approximately 75-100 measurements were taken for each measurement point by manually clicking on a button in the software program. Measurements were taken at random intervals (to capture a wide range of illuminance levels) as well as when the LEDs appeared to be at their peak output.

4.1.2 Procedure B

In the second procedure, referred to as Procedure B, the ASTM Standard Specification D4280-04, Extended Life Type, Nonplowable, Raised-Retroreflective Pavement Markers was used to measure the illuminance of SRPMs (*ASTM 2004*).

ASTM measurements were made for all samples except for those that were stud mounted and those that did not have any retroreflective material. In the latter case, ASTM measurements were unnecessary, since ASTM D4280 was not established as an LED-based standard. Table 4.3 gives the ASTM D4280 geometries.

Table 4.3: ASTM D4280 Goniometer System of Angles

α	β1	β2	ε
0.2	0	-20	0
0.2	0	0	0
0.2	0	20	0

4.2 TEST RESULTS

The measurements taken for all samples are shown in Tables 4.4 through 4.7. Using Procedure B, ASTM measurements were made for all samples except for Markers #3 and 4 (stud-mounted) and Marker #10. The latter did not have any retroreflective material (LEDs only); therefore ASTM measurements were unnecessary since ASTM D4280 was not established as an LED-based standard. Detailed results are available along with an electronic copy this report online at http://www.oregon.gov/ODOT/TD/TP_RES/ReportsbyYear.shtml#2008.

Using Procedure A, CIE edgeline measurements were made for Markers #5 and 6 as well as for Markers #13 and 14. Most of the measurements from the ASTM D4280 procedure failed to meet current ASTM minimum retroreflective standards. There are no pass/fail criteria for measurements made using the CIE goniometric system. These measurements were made to permit comparison of the photometric performance with the Observation Test done by ODOT. The measurement points established in Procedure A replicated the real world illumination and observation geometries of markers located at distances of 164, 328, 656, and 984 feet (50, 100, 200, and 300 meters) from a standard vehicle. The standard vehicle used is the CIE 54 1982 Car (*CIE 2001*). Note however that the average observation angle at a distance of 328 feet (200 meters) is very close to the standard observation angle (α) used in ASTM D4280, and the entrance angle components (β_1 and β_2) are small. Thus, the performance of a marker under the CIE goniometric system at 328 feet (200 meters) should be similar to measurement using ASTM D4280 with β_1 and β_2 both equal to 0.

Table 4.4: Results for RRPMs tested by FHWA – Markers 5 and 6

Procedure A: Markers 5 and 6						Retro (cd/lux)		LED Signal (cd)	
		CIE Goniometer System				White	Yellow	White	Yellow
Dist. (m)	**Headlight**	α	β_1	β_2	ε				
300	Left	0.11	-0.19	-0.18	19.35	0.003	0.010	1.56	0.35
300	Right	0.19	0.29	-0.34	-56.19	0.009	0.008	1.39	0.32
200	Left	0.16	-0.29	-0.28	19.03	0.004	0.009	1.58	0.36
200	Right	0.28	0.44	-0.51	-56.54	0.011	0.008	1.44	0.33
100	Left	0.32	-0.57	-0.57	18.05	0.008	0.008	1.63	0.36
100	Right	0.56	0.89	-1.00	-59.5	0.009	0.010	1.52	0.32
50	Left	0.60	-1.10	-1.17	15.97	0.004	0.010	1.74	0.35
50	Right	1.14	1.85	-1.94	-59.5	-0.003	0.010	1.67	0.33
Procedure B: Markers 5 and 6						Retro (cd/lux)			
D4280 Rqmts		**ASTM D4280 Measurements**				White	Yellow		
White	**Yellow**	α	β_1	β_2	ε				
0.112	0.067	0.2	0	-20	0	0.000	0.001		
0.279	0.167	0.2	0	0	0	-0.001	0.010		
0.112	0.067	0.2	0	20	0	0.000	0.001		

Note: Negative values indicate that the retroreflective signal was too low to be reliably measured at 16+ meters under an illumination of approximately 8.7 lux.

Table 4.5: Results for RRPMs tested by FHWA – Marker 10

Procedure A: Marker 10						LED Signal (cd)		
		CIE Goniometer System				White	Yellow	Yellow
Dist. (m)	**Headlight**	α	β_1	β_2	ε			
300	Left	0.11	-0.19	-0.18	19.35	5.21	1.01	0.99
300	Right	0.19	0.29	-0.34	-56.19	4.98	0.96	0.94
200	Left	0.16	-0.29	-0.28	19.03	5.92	1.04	1.02
200	Right	0.28	0.44	-0.51	-56.54	5.12	1.00	0.97
100	Left	0.32	-0.57	-0.57	18.05	5.68	1.12	1.08
100	Right	0.56	0.89	-1.00	-59.5	5.51	1.08	1.04
50	Left	0.60	-1.10	-1.17	15.97	9.40	1.74	1.67
50	Right	1.14	1.85	-1.94	-59.5	7.64	1.67	1.60

Note: These items did not have retroreflective material, so only the LED signal is provided, and only at the CIE geometry. The second column of values for the yellow devices is provided as a check of the initially measured values.

Table 4.6: Results for RRPMs tested by FHWA – Markers 13 and 14

Procedure A: Marker Numbers 13 and 14						Retro (cd/lux)		LED Signal (cd)	
		CIE Goniometer System				White	Yellow	White	Yellow
Dist. (m)	**Headlight**	α	β_1	β_2	ε				
300	Left	0.11	-0.19	-0.18	19.35	0.065	0.025	0.08	0.14
300	Right	0.19	0.29	-0.34	-56.19	0.059	0.024	0.08	0.13
200	Left	0.16	-0.29	-0.28	19.03	0.066	0.027	0.08	0.14
200	Right	0.28	0.44	-0.51	-56.54	0.058	0.026	0.08	0.14
100	Left	0.32	-0.57	-0.57	18.05	0.070	0.030	0.08	0.14
100	Right	0.56	0.89	-1.00	-59.5	0.045	0.025	0.08	0.14
50	Left	0.60	-1.10	-1.17	15.97	0.069	0.031	0.11	0.16
50	Right	1.14	1.85	-1.94	-59.5	0.016	0.009	0.10	0.15
Procedure B: Marker Numbers 13 and 14						Retro (cd/lux)			
D4280 Rqmts		**ASTM D4280 Measurements**				White	Yellow		
White	**Yellow**	α	β_1	β_2	ε				
0.112	0.067	0.2	0	-20	0	0.038	0.017		
0.279	0.167	0.2	0	0	0	0.065	0.025		
0.112	0.067	0.2	0	20	0	0.042	0.017		

Table 4.7: Results for RRPMs tested by FHWA – Markers 15 and 16

Procedure A: Marker Numbers 15 and 16						Retro (cd/lux)		LED Signal (cd)	
		CIE Goniometer System				White	Yellow	White	Yellow
Dist. (m)	**Headlight**	α	β_1	β_2	ε				
300	Left	0.11	-0.19	-0.18	19.35	0.247	0.134	2.35	0.56
300	Right	0.19	0.29	-0.34	-56.19	0.203	0.111	2.21	0.59
200	Left	0.16	-0.29	-0.28	19.03	0.247	0.134	2.53	0.53
200	Right	0.28	0.44	-0.51	-56.54	0.171	0.092	2.27	0.61
100	Left	0.32	-0.57	-0.57	18.05	0.222	0.117	2.52	0.54
100	Right	0.56	0.89	-1.00	-59.5	0.082	0.042	2.23	0.56
50	Left	0.60	-1.10	-1.17	15.97	0.141	0.075	2.69	0.47
50	Right	1.14	1.85	-1.94	-59.5	0.011	0.006	2.65	0.51
Procedure B: Marker Numbers 15 and 16						Retro (cd/lux)			
D4280 Rqmts		**ASTM D4280 Measurements**				White	Yellow		
White	**Yellow**	α	β_1	β_2	ε				
0.112	0.067	0.2	0	-20	0	0.136	0.072		
0.279	0.167	0.2	0	0	0	0.258	0.135		
0.112	0.067	0.2	0	20	0	0.152	0.080		

Each type of marker had significant shortcomings. The following summarizes the results for tests to measure retroreflected light, light emitted from LEDs, and the combined signal.

4.2.1 Coefficient of Retroreflected Intensity (R_I)

The test results indicated the following:

- Markers #5 and 6 had very low values of R_I. The uncertainty in the measurements made at 52+ feet (16+ meters), with an illumination on the marker of approximately 8.6 lux, resulted in some negative values of R_I. This indicates that the retroreflected illuminance provided by the SRPM was less than the uncertainty in the measurements.

- Markers #13 and 14 had values of R_I for white that ranged from 33% of the ASTM requirements at $\beta_2 = \pm 20$ degrees to 25% of the ASTM requirements at $\beta_2 = 0$ degrees. The values for yellow ranged from 25% at $\beta_2 = \pm 20$ degrees to 15% at $\beta_2 = 0$ degrees.

- Markers #15 and 16 met the requirements for R_I at $\beta_2 = \pm 20$ degrees for both white and yellow markers, but only provided 80% to 90% of the requirement at $\beta_2 = 0$ degrees.

- The R_I values for Markers #13 through 16, measured using the CIE goniometric system at a distance of 328 feet (200 meters), are substantially in agreement with the measurements made under ASTM D4280 at $\beta_2 = 0$ degrees.

4.2.2 Emitted light from LEDs

For the range of geometries selected, the light output from the LEDs is not as dependent on the observation angle as is R_I, the retroreflected intensity. Thus, when observed at close distances, the proportion of the signal from the LEDs will be greater than when they are observed at long distances. Assuming that a vehicle headlamp will provide an illuminance of 1 lux on the face of the markers at a distance of 200 meters, an LED output of 1 cd is equivalent to a R_I of 1.0 cd/lux. This is 3.6 times the required value of 0.279 for the R_I of a white marker, and 7.4 times the requirement for yellow when $\beta_2 = 0$ degrees. With the exception of Marker #10, the luminous intensity of the yellow LEDs was approximately 20% of the luminous intensity of the white LEDs.

- Markers #5 and 6 provided an LED output of 1.39 to 1.74 cd for white, and 0.32 to 0.35 cd for yellow.

- Marker #10 did not have a retroreflective component, and it provided the highest LED output of the sample SRPMs. The values for white ranged from 4.98 to 9.40 cd, with the highest values recorded at the closest road distance of 164 feet (50 meters). The yellow LEDs provided between 0.96 to 1.74 cd, again with the highest recorded values at the closest road distance. A second set of measurements of the yellow LEDs for Marker #10 indicated reasonably good consistency, with differences between the measurements of 2.0% to 4.4%.

- Markers #13 and 14 had very low LED outputs, which was observable in the laboratory. The measured values ranged from 0.08 to 0.11 cd for white and 0.13 to 0.16 cd for yellow. This was the only set in which the output from the yellow LEDs was higher than that of the white LEDs.

- Markers 15 and 16 had the flashing LEDs. The peak output of the LEDs was measured as being 2.21 to 2.69 cd for white and 0.47 to 0.61 cd for yellow.

4.2.3 Combined signal

The contribution of each component of the SRPM signal to the driver is based on the 328 foot (200 meter) road distance, and an assumed total illuminance provided by the vehicle's headlamps at the marker face of 1.0 lux. The requirements from ASTM D4280 at $\alpha = 0.2$ degrees and $\beta_1 = 0$ degrees and $\beta_2 = 0$ degrees are used for establishing a benchmark for the comparisons.

- Markers #5 and 6 had LED signals that were 5.4 times the requirement for white retroreflective signals and 2.0 times the requirement for yellow. The contribution of the retroreflective elements, however, was negligible.

- Marker #10 did not have any retroreflective elements. The LEDs provided signals that were 19.8 times the requirement for white and 6.1 times the requirement for yellow.

- Markers #13 and 14 had negligible contributions from the LEDs, and the retroreflective elements provided only 16% to 22% of the requirements.

- Markers #15 and 16 had LED signals that were 8.6 times the requirement for white and 3.4 times the requirement for yellow, at peak output. The LEDs were flashed, so the effective signal would be somewhat less. The retroreflective elements provided 75% and 68% of the requirements for white and yellow, respectively, at the road distance of 200 meters. Using ASTM D4280 measurement geometries, the retroreflective elements provided 90% to 80% of the requirements for white and yellow, respectively.

Based on the tests performed at the Photometric and Visibility Laboratory at the Turner-Fairbank Highway Research Center, it was concluded that each type of marker had significant shortcomings and that no further testing was justified.

5.0 FIELD TESTS

5.1 WEATHER TESTS

To gain a better understanding of how well the markers could be expected to perform under the typical seasonal changes in weather in Oregon a weather test was initiated in April 2007.

One of each marker was placed on a display board which was then placed in a fenced area adjacent to the ODOT's Materials Laboratory.

A one-year testing period had been planned so that a determination could be made about how well the markers would perform under different levels of solar exposure. However, when the results from the testing done at the Turner-Fairbank Highway Research Center revealed that no marker that was tested met ODOT's requirements, the weather test was terminated after eight months.

At the time the weather test was terminated, less than half of the markers were operating satisfactorily. At approximately an hour before sunrise, Markers #1, 3, 4, 13, 14, and 16 were operating satisfactorily. Markers #5 and 6 were lit but were very dim; Marker #6 had only two of three LEDs lit. The rest of the markers were not lit.

5.2 FIELD TRIALS

ODOT researchers had solicited suggestions for locations that would be appropriate for performing field trials. Locations were sought where other traffic control devices had not performed well due to road geometry and where, ideally, there was crash data to support the need for pavement marking material that would be more visible under extreme weather or lighting conditions. Such locations might be where the road curvature and terrain was such that headlights of approaching cars would not shine directly on the marker, or locations that experienced frequent heavy fog. At the time the decision was made to terminate any further testing and suspend the research project, no locations meeting these criteria had been confirmed. Thus no field trials were initiated.

6.0 SUMMARY OF FINDINGS AND RECOMMENDATIONS

6.1 SUMMARY OF FINDINGS

The major findings of this study are summarized below.

1. None of the solar-powered raised pavement markers tested by FHWA met ODOT's retroreflectivity standards. (Markers #15 and 16 met the standard at an angle of 20°, but not at 0°. The output of the LEDs was not sufficient to compensate for the low retroreflectivity values recorded.

2. Chromaticity tests revealed that many of the markers did not meet ASTM standards.

3. Most markers performed well in the environmental tests, which were more severe than those called for in the ASTM standards. Some showed damage after immersion. Weather tests indicated that prolonged exposure can result in failure after a short time period.

4. Some markers did not stay lit long enough in laboratory testing to warrant the conclusion that they would stay on during the longest period of darkness in Oregon (about 15 hours). This was confirmed by weather tests that were performed from April through December 2007, which showed that only six of the markers operated all night in mid-December.

5. Markers placed in a 2004 demonstration project were operating satisfactorily. No objective evaluation of these markers was performed, but comments from ODOT staff and the public indicate that the markers were operating and providing guidance to motorists.

6. ODOT lacked the testing equipment and specific technical expertise to complete all the tests required for this research study. Fortunately engineers at the Photometric and Visibility Laboratory (PVL) at the Turner-Fairbank Highway Research Center were able to perform supplemental testing on some of the markers.

7. ODOT was not able to identify locations for a field test that would be suitable for testing markers prior to the termination of the project. Test sites were sought where other traffic control devices had not performed well due to road geometry and where, ideally, there was crash data to support the need for pavement marking material that would be more visible under extreme weather or lighting conditions.

6.2 RECOMMENDATIONS

Based on the findings and conclusions of the study, the following recommendations are warranted:

1. The current specifications for RPMs should be updated to reflect current ASTM standards.

2. Due to performance concerns of the SRPMs tested in this research report, SRPMs should not be used in place of RRPMs that are currently approved for installation on highways in Oregon. It is expected that additional products will become available and that there will be improvements in the models tested. Before any markers are installed they should be tested to determine that minimum requirements are met. These include environmental tests, minimum retroreflectivity, and at least minimal observation tests.

3. Models installed should be given conditional QPL approval for a period of at least a year. If performance is satisfactory and markers can meet the basic requirements after a period of a year, they could be included on the QPL.

4. ODOT should encourage and help financially support research on new types and new applications of traffic control devices through pooled fund projects or similar funding approaches. Undertaking this type of research independently is costly and can be more effectively accomplished by pooling resources with others.

7.0 REFERENCES

ASTM International. *Standard Practice for Measuring Photometric Characteristics of Retroreflectors* (E809-02). American Society for Testing and Materials. West Conshohocken, PA. 2002.

ASTM International. *Standard Specification for Extended Life Type, Nonplowable, Prismatic, Raised, Retroreflective Pavement Markers* (D4280-04). American Society for Testing and Materials. West Conshohocken, PA. 2004.

Astucia Traffic Safety Systems. News release: "Astucia Gains UK Department of Transport Approval for Solarlite S Series MK11 Road Stud." http://www.astucia.co.uk/. Accessed July 11, 2005.

Bahar, G., C. Mollett, B. Persaud; C. Lyon, S. Smiley, T. Smahel, and H. McGee. Safety Evaluation of Permanent Raised Pavement Markers. National Cooperative Highway Research Program. Report No. 518. Transportation Research Board. Washington, DC. 2004.

Bahar, G., M. Masliah, T. Erwin, E. Tan, and E. Hauer. Pavement Marking Materials and Markers: Real-World Relationship Between Retroreflectivity and Safety Over Time. National Cooperative Highway Research Program. Web-Only Document No. 92. Transportation Research Board. Washington, DC. 2006.

Commission Internationale de l'Éclairage (CIE). Retroreflection: Definition and Measurement. Technical Report CIE 54.2 - 2001. Vienna, Austria. 2001.

Crawford, David. Red Light for Red Spots. ITS International. Volume 11, No. 2. 2005.

Federal Highway Administration (FHWA). *Manual on Uniform Traffic Control Devices for Streets and Highways*. 2003 Edition. Federal Highway Administration. Washington, DC. 2003.

Froese, Jerry. Senior Traffic Engineer, British Columbia Ministry of Transportation. Victoria, BC. Canada. Telephone conversation, November 15, 2006.

Grant, A.R. and J.R. Bloomfield. Guidelines for the Use of Raised Pavement Markers. Report No. FHWA-RD-97-152. Federal Highway Administration. University of Iowa. Center for Computer Aided Design. Iowa City, IA. 1998.

Institute of Transportation Engineers. Solar roadway pavement markings. *ITE Journal*. June 1997.

ITEM, Ltd. Highway #7: Mission, BC. http://www.itemltd.com/products/solarmarker/installations/Mission.html. Accessed June 6, 2006.

Meyer, E. *Solar Powered Illuminated RPMs*. Midwest Smart Work Zone Development Initiative. University of Kansas. Lawrence, KS. 2000.

Migletz, J., J.K. Fish and J.L. Graham. *The Roadway Delineation Practices Handbook*. Report No. FHWA-SA-93-001. Office of Safety and Office of Technology Applications. Federal Highway Administration. 1994.

Migletz, J. and J.L. Graham. *Long-Term Pavement Marking Practices Transportation. National Cooperative Highway Research Program*. Synthesis 306. Transportation Research Board. Washington, DC. 2002.

Munehiro, K, R.A. Tokunaga, M. Asano, and T. Hagiwara. Required Luminous Intensity of LED Delineators Under Foggy Conditions. Transportation Research Board 85th Annual Meeting. Washington, DC. 2006.

National Cooperative Highway Research Program (NCHRP). Project 20-5, Topic 38-13. Illuminated, Active In-Pavement Marker Systems. Scope of Work. 2006.

Reed, N. Driver Behaviour in Response to Actively Illuminated Road Studs: A Simulator Study. TRL Limited. Berkshire, RG40 3GA, United Kingdom. 2006.

Styles, T., P. Cairney, G. Studwick, and S. Purtill. 2003. Trial and Evaluation of Internally Illuminated Pavement Markers. *Road &Transport*. March 2004.

APPENDICES

APPENDIX A: STANDARD GUIDELINES FOR PRODUCT REVIEW: PAVEMENT MARKERS, TYPE 1

Standard Guidelines for Product Review

PAVEMENT MARKERS, TYPE 1;
Section 02840.60

July 18, 2000

Oregon
DEPARTMENT OF TRANSPORTATION
Construction Section
800 Airport Road SE
Salem, OR 97301-4798
503/986-3059

02840.60 – Pavement Markers, Type I:

Description - Type I pavement markers are reflectorized. The markers are surface mounted and shall be:

1. Not more than 4.5 inches (120 mm) wide.
2. Be able to adhere to asphalt or concrete surfaces with bituminous or epoxy adhesives.

Process - Submit the following:

- Preliminary Information for Product Evaluation Form.
- Independent Test Results showing compliance with Specs listed below.
- Product Data Sheet.
- Detailed installation instructions.
- List of Limitations and Precautions.
- Submit 15 markers for our evaluation (each color).

Specifications - Strength, Optical Performance, Pull-Off:

Strength Requirements:

(1) Method Of Test - Select 3 specimens of any type of marker for load testing. Place each 100 mm x 100 mm marker on an "Alert 15175" pad, 7 mm thick, 17 ply, or equivalent and centered over the open end of a vertically positioned hollow cylinder that is 25 mm high with an internal diameter of 75 mm and a wall thickness of 6 mm. Place each 50 mm x 100 mm marker directly on a 12 mm thick flat steel plate. Apply a load necessary to break the marker at a speed of 5 mm/min to the top of the marker through a 25 mm diameter solid metal cylinder centered on the top of the marker.

(2) Requirements - Failure of the marker shall be determined as either breakage, deformation, or delamination of the shell and filler material at a load less than 680 kg for the 100 mm x 100 mm markers and 1800 kg for the 50 mm x 100 mm markers.

(3) Retest - Should any one of the 3 markers selected for strength testing fail to comply with the strength requirements of this specification, 6 additional specimens will be tested. The failure of any one of these 6 specimens shall be cause for the rejection of the entire lot or shipment represented by this sample.

Oregon
DEPARTMENT OF
TRANSPORTATION
Construction Section
800 Airport Road SE
Salem, OR 97301-4798
503/986-3059

Optical Performance - Test three markers of each color according to Federal Test Method Standard 370. The luminous intensity of each reflective surface, when tested at 0.2° observation angle shall not be less than the following specified value:

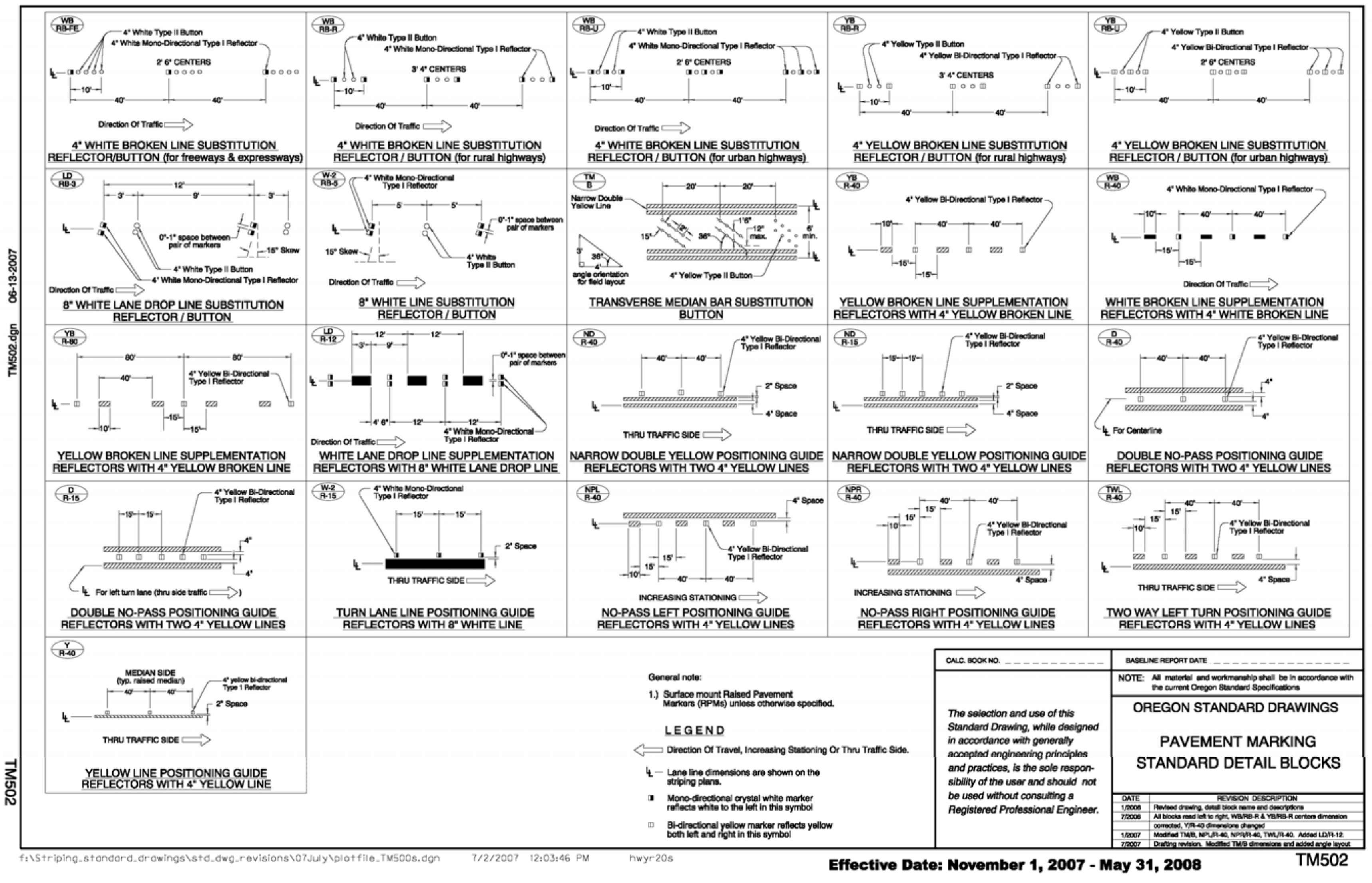
	Coefficient of Luminous Intensity (R_I), cd/lx	
Entrance Angle	**White**	**Yellow**
0°	3.0	1.5
20°	1.2	0.6

Pull-Off Bond Test - Provide markers with bottom surfaces capable of good bond to adhesive. Five specimens shall be tested and shall provide a minimum average tensile bond strength of 3.4 MPa. The test consists of bonding a 38 mm diameter steel test plug with sandblasted surface to the center of the marker bottom using an epoxy meeting the requirements of AASHTO M237. After 48 hours curing time at 23 °C ± 2 °C the test plugs shall be tensile loaded at a rate of 2200 kg/min to failure.

Please forward your request and/or questions to:

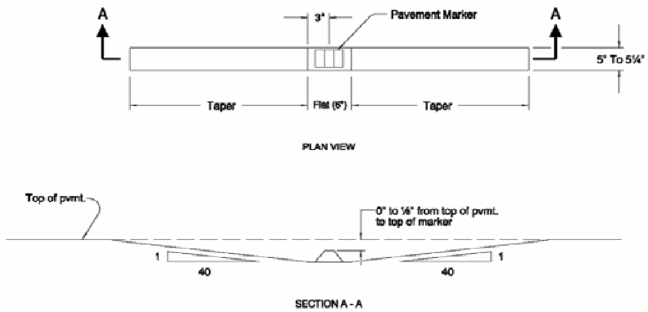
OREGON DEPARTMENT OF TRANSPORTATION
ATTN: MIKE DUNNING (503) 986-3059
MATERIALS LABORATORY
800 AIRPORT RD SE
Salem Or 97301-4798

APPENDIX B: RAISED PAVEMENT MARKER STANDARD DRAWINGS

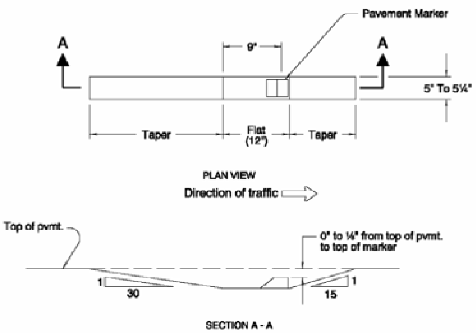


WB RB-FE
4" WHITE BROKEN LINE SUBSTITUTION REFLECTOR/BUTTON (for freeways & expressways)
WB RB-R
4" WHITE BROKEN LINE SUBSTITUTION REFLECTOR / BUTTON (for rural highways)
WB RB-U
4" WHITE BROKEN LINE SUBSTITUTION REFLECTOR / BUTTON (for urban highways)
YB RB-R
4" YELLOW BROKEN LINE SUBSTITUTION REFLECTOR / BUTTON (for rural highways)
YB RB-U
4" YELLOW BROKEN LINE SUBSTITUTION REFLECTOR / BUTTON (for urban highways)
LD RB-3
8" WHITE LANE DROP LINE SUBSTITUTION REFLECTOR / BUTTON
W-2 RB-5
8" WHITE LINE SUBSTITUTION REFLECTOR / BUTTON
TM B
TRANSVERSE MEDIAN BAR SUBSTITUTION BUTTON
YB R-40
YELLOW BROKEN LINE SUPPLEMENTATION REFLECTORS WITH 4" YELLOW BROKEN LINE
WB R-40
WHITE BROKEN LINE SUPPLEMENTATION REFLECTORS WITH 4" WHITE BROKEN LINE
YB R-80
YELLOW BROKEN LINE SUPPLEMENTATION REFLECTORS WITH 4" YELLOW BROKEN LINE
LD R-12
WHITE LANE DROP LINE SUPPLEMENTATION REFLECTORS WITH 8" WHITE LANE DROP LINE
ND R-40
NARROW DOUBLE YELLOW POSITIONING GUIDE REFLECTORS WITH TWO 4" YELLOW LINES
ND R-15
NARROW DOUBLE YELLOW POSITIONING GUIDE REFLECTORS WITH TWO 4" YELLOW LINES
D R-40
DOUBLE NO-PASS POSITIONING GUIDE REFLECTORS WITH TWO 4" YELLOW LINES
D R-15
DOUBLE NO-PASS POSITIONING GUIDE REFLECTORS WITH TWO 4" YELLOW LINES
W-2 R-15
TURN LANE LINE POSITIONING GUIDE REFLECTORS WITH 8" WHITE LINE
NPL R-40
NO-PASS LEFT POSITIONING GUIDE REFLECTORS WITH 4" YELLOW LINES
NPR R-40
NO-PASS RIGHT POSITIONING GUIDE REFLECTORS WITH 4" YELLOW LINES
TWL R-40
TWO WAY LEFT TURN POSITIONING GUIDE REFLECTORS WITH 4" YELLOW LINES
Y R-40
YELLOW LINE POSITIONING GUIDE REFLECTORS WITH 4" YELLOW LINE
General note:
1.) Surface mount Raised Pavement Markers (RPMs) unless otherwise specified.
LEGEND
Direction Of Travel, Increasing Stationing Or Thru Traffic Side.
Lane line dimensions are shown on the striping plans.
Mono-directional crystal white marker reflects white to the left in this symbol
Bi-directional yellow marker reflects yellow both left and right in this symbol
CALC. BOOK NO.
BASELINE REPORT DATE
NOTE: All material and workmanship shall be in accordance with the current Oregon Standard Specifications
The selection and use of this Standard Drawing, while designed in accordance with generally accepted engineering principles and practices, is the sole responsibility of the user and should not be used without consulting a Registered Professional Engineer.
OREGON STANDARD DRAWINGS
PAVEMENT MARKING STANDARD DETAIL BLOCKS
DATE
REVISION DESCRIPTION
TM502.dgn 06-13-2007
TM502
f:\Striping_standard_drawings\std_dwg_revisions\07July\plotfile_TM500s.dgn 7/2/2007 12:03:46 PM hwyr20s
Effective Date: November 1, 2007 - May 31, 2008
TM502

TM517.dgn 06-13-2007



BI-DIRECTIONAL RECESSED PAVEMENT MARKER DETAIL



MONO-DIRECTIONAL RECESSED PAVEMENT MARKER DETAIL

TM517

LEGEND

⇦ Direction of Travel

CALC. BOOK NO. ____________

The selection and use of this Standard Drawing, while designed in accordance with generally accepted engineering principles and practices, is the sole responsibility of the user and should not be used without consulting a Registered Professional Engineer.

BASELINE REPORT DATE ________________

NOTE: All material and workmanship shall be in accordance with the current Oregon Standard Specifications

OREGON STANDARD DRAWINGS

RECESSED PAVEMENT MARKERS

DATE	REVISION DESCRIPTION
1/2007	New Drawing - Detail from TM515 moved to TM517
7/2007	Drafting revision

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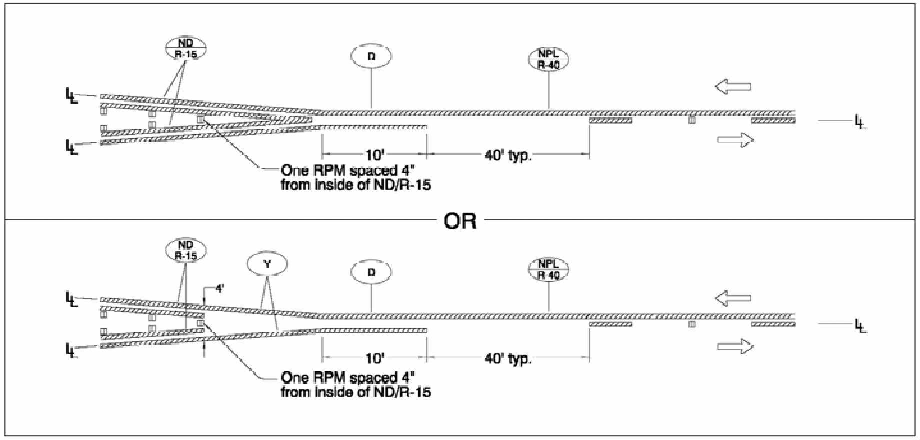
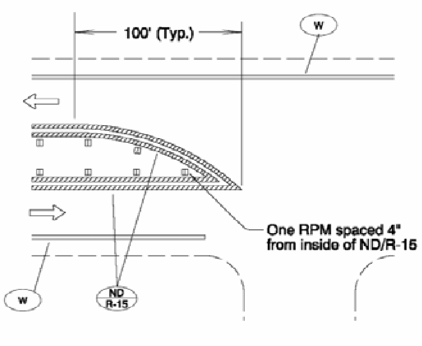
Effective Date: November 1, 2007 - May 31, 2008

TM517

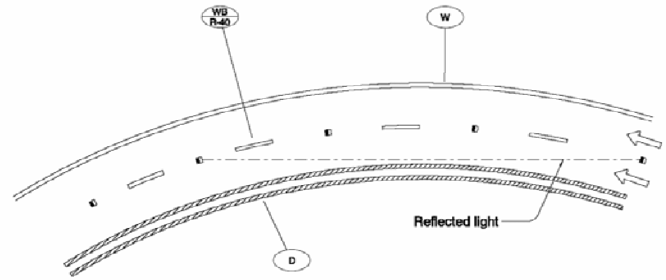


MEDIAN WIDTH TRANSITION

(TWO NARROW DOUBLE YELLOW LINES TO ONE-DIRECTION NO-PASSING LINE)

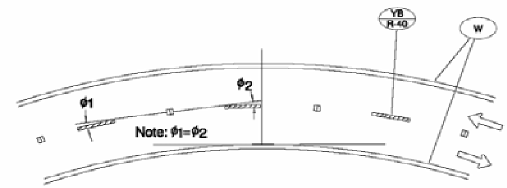


MEDIAN BULLNOSE DETAIL



NOTE:
On one way sections the marker shall be installed with the reflective surface aimed to direct the reflected light back three markers.

(a) PAVEMENT MARKER INSTALLATION FOR WHITE BROKEN LINE SUPPLEMENTATION



PAVEMENT MARKER INSTALLATION ON HORIZONTAL CURVES

(b) PAVEMENT MARKER INSTALLATION FOR YELLOW BROKEN LINE SUPPLEMENTATION

LEGEND

- Mono-Directional White (marker reflects white to left in this symbol)
- Bi-Directional Yellow (marker reflects yellow to both the left and right in this symbol)
- Increasing stationing from left to right
- ⇐ Direction of Travel
- ℄ — Lane line dimensions are shown on the striping plans.

To be accompanied by Standard Dwg. Nos. TM500 thru TM503

CALC. BOOK NO. ____________

BASELINE REPORT DATE ____________

NOTE: All material and workmanship shall be in accordance with the current Oregon Standard Specifications

The selection and use of this Standard Drawing, while designed in accordance with generally accepted engineering principles and practices, is the sole responsibility of the user and should not be used without consulting a Registered Professional Engineer.

OREGON STANDARD DRAWINGS

RAISED PAVEMENT MARKERS

DATE	REVISION DESCRIPTION
1/2006	New Drawing (consolidated & clarified information from old TM std. dwgs.)
7/2006	Replaced text with bubble notes. Added freeway crossover marking detail
	Modified recessed pavement marker details
1/2007	Moved details to TM516 & TM517. Added left turn lane detail.
7/2007	Drafting revision. Deleted design details contained in the TLM. Added bullnose

TM515.dgn 06-13-2007

TM515

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Effective Date: November 1, 2007 - May 31, 2008

TM515

APPENDIX C: SURVEY OF STATES QUESTIONNAIRE AND RESULTS

RAC Questionnaire

Question Number	Question
1	Does your department use solar-powered pavement/barrier markers on state or federal highways?
2	If so, do you have specifications for their use (i.e. roadway geometry or weather restrictions, etc.)?
3	What is your opinion on their performance?
4	Has your department published any research or study on their performance? If so, please list:
5	Have you read or seen any research/study publications related to this type of markers? If so, please list:
6	In general, would you recommend other DOT's to use them as an effective traffic control device?

RAC Questionnaire Responses Summary

State	Uses?	Ever Used?	Research/Study	Comments
AR	N	N	N	
AZ	N	N	N	
CT	N	N	N	
GA	N	N	N	
IA	N	N	N	
IL	N	N	N	
KS	N	N	N	
MN	N	N	N	
MS	N	N	N	
NE	N	N	N	
NV	N	N	N	
NY	N	N	N	
OH	N	N	N	
SD	N	N	N	
TN	N	N	N	
TX	Y	Y	N	They use them on state highways for product evaluations. Their testing is focused on durability and not performance with respect to driver behavior. So far, they have not published any reports but they report that several markers have been stolen. They also believe that independent research needs to be done and they foresee widespread use of them in the future
WA	N	N	N	
WI	N	N	N	Existing policy on non solar-powered in-roadway warning lights
WV	N	N	From vendors and manufacturers only	Although particular industries push this type of device, we do not have any practical experience with these devices. Since we are a 'snow-belt' state, we primarily use low-profile, snow-plowable pavement markers, as such, I'm very apprehensive of using markers that may employ any integral solar-power design…it is hard enough to keep our retroreflective markers in place. I'm very concerned about continuing maintenance with many of these markers which I would think may impact our return of investment in placing this type of marker.
WY	N	N	N	

APPENDIX D: SOLAR-POWERED RAISED PAVEMENT MARKER TESTING PROTOCOL-LABORATORY TEST RESULTS

	TEST	Product 1	Product 2	Product 3
1.0	**Manufacturer's Specifications and Confirmation**			
	Test Description: Record information from manufacturer and confirm by actual measurement.			
1.1	length (in inches)	3.94	3.94	5.25
1.2	width (in inches; must be no more than 4.5 inches wide)	3.94	3.94	4.88
1.3	heigth (in inches)	0.813	0.813	0.813
1.4	Color of display	white	amber	white
1.5	Number of LEDs	2	2	2
1.6	Power backup	CAP	CAP	CAP
1.7	Operating temperature range (°C)	-40 to 80	-40 to 80	-40 to 80
1.8	Luminance level (mcd)	5000	5000	5000
1.9	Visibility range (in feet)	3200	3200	3200
	Two of each product are to be tested. They should be randomly labeled by Product Number and Group "A" and "B".			
2.0	**Environmental Tests**			
2.1	**Extreme temperatures**			
	Test Description: Raise or lower temperature (at a rate not more than 16 ° per hour) in TSSU			
	Environmental Testing Chamber to extreme limits and maintain for 12 hours.			
	Record date/time of tests. Observe performance at extremes.			
2.1.1	Low temperature (-34° C)			
2.1.2	High temperature (73° C)			
2.2	**Immersion Test**			
	Test description: Put marker in water for 24 hours and observe that no apparent moisture intrusion occurred.			
2.3	**Post-Test Evaluation**			
	Fully charge all markers, place in dark. Check visibility after 12, 16, and 20 hours. It is desirable that display			
	is still visible after 16 hours.			

	TEST	Product 1	Product 2	Product 3
3.0	**Optical Performance**			
3.1	**Test 1 Description**: Determine test time. At least 24 hours before the test expose one of each product to ideal	**A**	**A**	**A**
	solar conditions (or incandescent light) for at least 8 hours. Remove and place where LED will remain on for 16 hours. **cd**	0.08	n/a	1.02
	Call this Group B. Expose one of each product to ideal solar conditions for at least 8 hours. Call this **X/Y**	0.297, 0.310	n/a	0.258, 0.252
	Group A. Conduct test on Group A as follows: Using the Photo Research PR 650 Photometer/Colorometer	**B**	**B**	**B**
	and adjusting for optimal performance record three candela and x and y color coordinate readings. **cd**	0.08	n/a	0.91
	Repeat for Group B markers. **X/Y**	0.309, 329	n/a	0.270, 0.272
	Meets ASTM 4280 color standards	yes	n/a	no
3.2	**Test 2.1 Description**: Follow above procedure to expose Group A and B products as above. Set products in			
	field so they may be viewed from 200 meters at an angle of 0° twice in different order. Have observers give			
	subjective evaluation of legibility on a scale of 1-5, with 5= excellent visibility, 4=good visibility, 3= fair visibility,			
	2=visible but not recommended for installation;1=not visible.			
	Average score for Group A for all observers must be 3.00.	2.67	2.44	2.94
	Average score for Group B for all observers must be 2.50	2.61	2.11	2.72
	Test 2.2 Description: Position groups of 3 or 4 markers from Group A at an angle of 20° have observers			
	indicate the distance at which light is visible and rate the visibility as above.			
	Average score for all observers must be 2.00 or better with no more than 25% of the observations from less than 150 m.	2.22	1.67	2.33
4.0	**Strength test and pull-off tests**			
	These tests are not required due to limited direct exposure to vehicles.			

	TEST	Product 4	Product 5	Product 6
1.0	**Manufacturer's Specifications and Confirmation**			
	Test Description: Record information from manufacturer and confirm by actual measurement.			
1.1	length (in inches)	5.25	3.94	3.94
1.2	width (in inches; must be no more than 4.5 inches wide)	4.88	3.94	3.94
1.3	heigth (in inches)	0.813	0.79	0.79
1.4	Color of display	amber	white	amber
1.5	Number of LEDs	2	3	3
1.6	Power backup	CAP	BAT	BAT
1.7	Operating temperature range (°C)	-40 to 80	N/A	N/A
1.8	Luminance level (mcd)	5000	N/A	N/A
1.9	Visibility range (in feet)	3200	N/A	N/A
	Two of each product are to be tested. They should be randomly labeled by Product Number and Group "A" and "B".			
2.0	**Environmental Tests**			
2.1	**Extreme temperatures**			
	Test Description: Raise or lower temperature (at a rate not more than 16 ° per hour) in TSSU			
	Environmental Testing Chamber to extreme limits and maintain for 12 hours.			
	Record date/time of tests. Observe performance at extremes.			
2.1.1	Low temperature (-34° C)		5A blinking -33°	
2.1.2	High temperature (73° C)			
2.2	**Immersion Test**			
	Test description: Put marker in water for 24 hours and observe that no apparent moisture intrusion occurred.	4A & B LED cldy; water drip by screws	5A & B LEDs cloudy	6A and B water visible in case; small crack
2.3	**Post-Test Evaluation**			
	Fully charge all markers, place in dark. Check visibility after 12, 16, and 20 hours. It is desirable that display			
	is still visible after 16 hours.		5A dim 16 hr	6A dim 16 hr
			5B off 12 hr	6B off 12 hr

	TEST	Product 4	Product 5	Product 6
3.0	**Optical Performance**			
3.1	**Test 1 Description**: Determine test time. At least 24 hours before the test expose one of each product to ideal	**A**	**A**	**A**
	solar conditions (or incandescent light) for at least 8 hours. Remove and place where LED will remain on for 16 hours. **cd**	0.04	3.41	4.45
	Call this Group B. Expose one of each product to ideal solar conditions for at least 8 hours. Call this **X/Y**	0.534,0.436	0.273, 0.262	0.586, 0.413
	Group A. Conduct test on Group A as follows: Using the Photo Research PR 650 Photometer/Colorometer	**B**	**B**	**B**
	and adjusting for optimal performance record three candela and x and y color coordinate readings. **cd**	0.04	1.57	0.4
	Repeat for Group B markers. **X/Y**	0.534, 0.436	0.276, 0.270	0.561, 0.416
	Meets ASTM 4280 color standards	yes	no	yes
3.2	**Test 2.1 Description**: Follow above procedure to expose Group A and B products as above. Set products in			
	field so they may be viewed from 200 meters at an angle of 0° twice in different order. Have observers give			
	subjective evaluation of legibility on a scale of 1-5, with 5= excellent visibility, 4=good visibility, 3= fair visibility,			
	2=visible but not recommended for installation;1=not visible.			
	Average score for Group A for all observers must be 3.00.	2.17	4.44	4.44
	Average score for Group B for all observers must be 2.50	2.28	3.83	2.94
	Test 2.2 Description: Position groups of 3 or 4 markers from Group A at an angle of 20° have observers			
	indicate the distance at which light is visible and rate the visibility as above.			
	Average score for all observers must be 2.00 or better with no more than 25% of the observations from less than 150 m.	1.56	2.33	2.11
4.0	**Strength test and pull-off tests**			
	These tests are not required due to limited direct exposure to vehicles.			

	TEST	Product 7	Product 8	Product 9
1.0	**Manufacturer's Specifications and Confirmation**			
	Test Description: Record information from manufacturer and confirm by actual measurement.			
1.1	length (in inches)	4	4	4.33
1.2	width (in inches; must be no more than 4.5 inches wide)	2	2	3.81
1.3	heigth (in inches)	0.52	0.52	0.96
1.4	Color of display	white	amber	amber
1.5	Number of LEDs	1	1	3
1.6	Power backup	Bat	Bat	BAT
1.7	Operating temperature range (°C)	-28 to 71	-28 to 71	N/A
1.8	Luminance level (mcd)	900	900	N/A
1.9	Visibility range (in feet)	N/A	N/A	3200
	Two of each product are to be tested. They should be randomly labeled by Product Number and Group "A" and "B".			
2.0	**Environmental Tests**			
2.1	**Extreme temperatures**			
	Test Description: Raise or lower temperature (at a rate not more than 16 ° per hour) in TSSU			
	Environmental Testing Chamber to extreme limits and maintain for 12 hours.			
	Record date/time of tests. Observe performance at extremes.			
2.1.1	Low temperature (-34° C)	7B off -14°	8A blink -32°	
2.1.2	High temperature (73° C)	7B relite 65°		
2.2	**Immersion Test**			
	Test description: Put marker in water for 24 hours and observe that no apparent moisture intrusion occurred.		8 B water in case	9A and B condensation LED lens
2.3	**Post-Test Evaluation**			
	Fully charge all markers, place in dark. Check visibility after 12, 16, and 20 hours. It is desirable that display			
	is still visible after 16 hours.	7B dim 12 hr		9A off 12 hr

	TEST	Product 7	Product 8	Product 9
3.0	**Optical Performance**			
3.1	**Test 1 Description**: Determine test time. At least 24 hours before the test expose one of each product to ideal	**A**	**A**	**A**
	solar conditions (or incandescent light) for at least 8 hours. Remove and place where LED will remain on for 16 hours. **cd**	2.61	0.71	N/A
	Call this Group B. Expose one of each product to ideal solar conditions for at least 8 hours. Call this **X/Y**	0.270,0.275	0.563, 0.430	N/A
	Group A. Conduct test on Group A as follows: Using the Photo Research PR 650 Photometer/Colorometer	**B**	**B**	**B**
	and adjusting for optimal performance record three candela and x and y color coordinate readings. **cd**	N/A	1.42	0.38
	Repeat for Group B markers. **X/Y**	N/A	0.561, 0.431	0.567,0.415
	Meets ASTM 4280 color standards	no	yes	yes
3.2	**Test 2.1 Description**: Follow above procedure to expose Group A and B products as above. Set products in			
	field so they may be viewed from 200 meters at an angle of 0° twice in different order. Have observers give			
	subjective evaluation of legibility on a scale of 1-5, with 5= excellent visibility, 4=good visibility, 3= fair visibility,			
	2=visible but not recommended for installation;1=not visible.			
	Average score for Group A for all observers must be 3.00.	3.83	2.89	1.00
	Average score for Group B for all observers must be 2.50	1.00	1.83	2.44
	Test 2.2 Description: Position groups of 3 or 4 markers from Group A at an angle of 20° have observers			
	indicate the distance at which light is visible and rate the visibility as above.			
	Average score for all observers must be 2.00 or better with no more than 25% of the observations from less than 150 m.	3.00	2.44	1.00
4.0	**Strength test and pull-off tests**			
	These tests are not required due to limited direct exposure to vehicles.			

	TEST	Product 10	Product 11	Product 12
1.0	**Manufacturer's Specifications and Confirmation**			
	Test Description: Record information from manufacturer and confirm by actual measurement.			
1.1	length (in inches)	4.33	4.3	4.3
1.2	width (in inches; must be no more than 4.5 inches wide)	3.81	3.8	3.8
1.3	heigth (in inches)	0.96	0.9	0.9
1.4	Color of display	amber	white	amber
1.5	Number of LEDs	3	2	2
1.6	Power backup	CAP	BAT	CAP
1.7	Operating temperature range (°C)	N/A	-3 to 70	-3 to 70
1.8	Luminance level (mcd)	N/A	N/A	N/A
1.9	Visibility range (in feet)	3200	1969	1969
	Two of each product are to be tested. They should be randomly labeled by Product Number and Group "A" and "B".			
2.0	**Environmental Tests**			
2.1	**Extreme temperatures**			
	Test Description: Raise or lower temperature (at a rate not more than 16 ° per hour) in TSSU			
	Environmental Testing Chamber to extreme limits and maintain for 12 hours.			
	Record date/time of tests. Observe performance at extremes.			
2.1.1	Low temperature (-34° C)	10 A&B dim -14°	11 A dim -14°	12B dim -32°
2.1.2	High temperature (73° C)			
2.2	**Immersion Test**			
	Test description: Put marker in water for 24 hours and observe that no apparent moisture intrusion occurred.			
2.3	**Post-Test Evaluation**			
	Fully charge all markers, place in dark. Check visibility after 12, 16, and 20 hours. It is desirable that display			
	is still visible after 16 hours.	10 A off 12 hr	11A & B dim 16hr	12A dim 12 hr
				12B off 12 hr

	TEST	Product 10	Product 11	Product 12
3.0	**Optical Performance**			
3.1	**Test 1 Description**: Determine test time. At least 24 hours before the test expose one of each product to ideal	**A**	**A**	**A**
	solar conditions (or incandescent light) for at least 8 hours. Remove and place where LED will remain on for 16 hours. **cd**	0.53	0.09	1.2
	Call this Group B. Expose one of each product to ideal solar conditions for at least 8 hours. Call this **X/Y**	0.569, 0.414	0.299, 0.316	0.550, 0.443
	Group A. Conduct test on Group A as follows: Using the Photo Research PR 650 Photometer/Colorometer	**B**	**B**	**B**
	and adjusting for optimal performance record three candela and x and y color coordinate readings. **cd**	0.04	N/A	N/A
	Repeat for Group B markers. **X/Y**	0.523, 0.415	N/A	N/A
	Meets ASTM 4280 color standards	yes	no	no
3.2	**Test 2.1 Description**: Follow above procedure to expose Group A and B products as above. Set products in			
	field so they may be viewed from 200 meters at an angle of 0° twice in different order. Have observers give			
	subjective evaluation of legibility on a scale of 1-5, with 5= excellent visibility, 4=good visibility, 3= fair visibility,			
	2=visible but not recommended for installation;1=not visible.			
	Average score for Group A for all observers must be 3.00.	3.06	2.67	2.78
	Average score for Group B for all observers must be 2.50	2.28	1.28	1.06
	Test 2.2 Description: Position groups of 3 or 4 markers from Group A at an angle of 20° have observers			
	indicate the distance at which light is visible and rate the visibility as above.			
	Average score for all observers must be 2.00 or better with no more than 25% of the observations from less than 150 m.	2.44	1.75	2.22
4.0	**Strength test and pull-off tests**			
	These tests are not required due to limited direct exposure to vehicles.			

	TEST	Product 13	Product 14	Product 15
1.0	**Manufacturer's Specifications and Confirmation**			
	Test Description: Record information from manufacturer and confirm by actual measurement.			
1.1	length (in inches)	3.94	3.94	4.73
1.2	width (in inches; must be no more than 4.5 inches wide)	3.94	3.94	3.94
1.3	heigth (in inches)	0.73	0.73	0.8
1.4	Color of display	white	amber	white
1.5	Number of LEDs	1	1	2
1.6	Power backup	BAT	BAT	CAP
1.7	Operating temperature range (°C)	N/A	N/A	-20 to 60
1.8	Luminance level (mcd)	N/A	N/A	5000
1.9	Visibility range (in feet)	3200	3200	5280
	Two of each product are to be tested. They should be randomly labeled by Product Number and Group "A" and "B".			
2.0	**Environmental Tests**			
2.1	**Extreme temperatures**			
	Test Description: Raise or lower temperature (at a rate not more than 16 ° per hour) in TSSU			
	Environmental Testing Chamber to extreme limits and maintain for 12 hours.			
	Record date/time of tests. Observe performance at extremes.			
2.1.1	Low temperature (-34° C)			
2.1.2	High temperature (73° C)			
2.2	**Immersion Test**			
	Test description: Put marker in water for 24 hours and observe that no apparent moisture intrusion occurred.			
2.3	**Post-Test Evaluation**			
	Fully charge all markers, place in dark. Check visibility after 12, 16, and 20 hours. It is desirable that display			
	is still visible after 16 hours.			15A & B dim 16 hr

	TEST	Product 13	Product 14	Product 15
3.0	**Optical Performance**			
3.1	**Test 1 Description**: Determine test time. At least 24 hours before the test expose one of each product to ideal	**A**	**A**	**A**
	solar conditions (or incandescent light) for at least 8 hours. Remove and place where LED will remain on for 16 hours. **cd**	0.06	0.44	0.11
	Call this Group B. Expose one of each product to ideal solar conditions for at least 8 hours. Call this **X/Y**	0.3, 0.307	0.360, 0.542	0.312, 0.316
	Group A. Conduct test on Group A as follows: Using the Photo Research PR 650 Photometer/Colorometer	**B**	**B**	**B**
	and adjusting for optimal performance record three candela and x and y color coordinate readings. **cd**	0.06	0.36	0.03
	Repeat for Group B markers. **X/Y**	0.300, 0.307	0.542, 0.436	0.316, 0.319
	Meets ASTM 4280 color standards	yes	no	yes
3.2	**Test 2.1 Description**: Follow above procedure to expose Group A and B products as above. Set products in			
	field so they may be viewed from 200 meters at an angle of 0° twice in different order. Have observers give			
	subjective evaluation of legibility on a scale of 1-5, with 5= excellent visibility, 4=good visibility, 3= fair visibility,			
	2=visible but not recommended for installation;1=not visible.			
	Average score for Group A for all observers must be 3.00.	2.56	2.94	4.61
	Average score for Group B for all observers must be 2.50	2.72	2.62	4.44
	Test 2.2 Description: Position groups of 3 or 4 markers from Group A at an angle of 20° have observers			
	indicate the distance at which light is visible and rate the visibility as above.			
	Average score for all observers must be 2.00 or better with no more than 25% of the observations from less than 150 m.	1.88	1.44	3.13
4.0	**Strength test and pull-off tests**			
	These tests are not required due to limited direct exposure to vehicles.			

	TEST	product 16
1.0	**Manufacturer's Specifications and Confirmation**	
	Test Description: Record information from manufacturer and confirm by actual measurement.	
1.1	length (in inches)	4.73
1.2	width (in inches; must be no more than 4.5 inches wide)	3.94
1.3	heigth (in inches)	0.8
1.4	Color of display	amber
1.5	Number of LEDs	2
1.6	Power backup	CAP
1.7	Operating temperature range (°C)	-20 to 60
1.8	Luminance level (mcd)	5000
1.9	Visibility range (in feet)	5280
	Two of each product are to be tested. They should be randomly labeled by Product Number and Group "A" and "B".	
2.0	**Environmental Tests**	
2.1	**Extreme temperatures**	
	Test Description: Raise or lower temperature (at a rate not more than 16 ° per hour) in TSSU	
	Environmental Testing Chamber to extreme limits and maintain for 12 hours.	
	Record date/time of tests. Observe performance at extremes.	
2.1.1	Low temperature (-34° C)	
2.1.2	High temperature (73° C)	
2.2	**Immersion Test**	
	Test description: Put marker in water for 24 hours and observe that no apparent moisture intrusion occurred.	16B condensation LED lens
2.3	**Post-Test Evaluation**	
	Fully charge all markers, place in dark. Check visibility after 12, 16, and 20 hours. It is desirable that display	
	is still visible after 16 hours.	

	TEST	product 16
3.0	**Optical Performance**	
3.1	**Test 1 Description**: Determine test time. At least 24 hours before the test expose one of each product to ideal	**A**
	solar conditions (or incandescent light) for at least 8 hours. Remove and place where LED will remain on for 16 hours. **cd**	0.05
	Call this Group B. Expose one of each product to ideal solar conditions for at least 8 hours. Call this **X/Y**	0.496, 0.410
	Group A. Conduct test on Group A as follows: Using the Photo Research PR 650 Photometer/Colorometer	**B**
	and adjusting for optimal performance record three candela and x and y color coordinate readings. **cd**	0.01
	Repeat for Group B markers. **X/Y**	0.562, 0.421
	Meets ASTM 4280 color standards	yes
3.2	**Test 2.1 Description**: Follow above procedure to expose Group A and B products as above. Set products in	
	field so they may be viewed from 200 meters at an angle of 0° twice in different order. Have observers give	
	subjective evaluation of legibility on a scale of 1-5, with 5= excellent visibility, 4=good visibility, 3= fair visibility,	
	2=visible but not recommended for installation;1=not visible.	
	Average score for Group A for all observers must be 3.00.	4.06
	Average score for Group B for all observers must be 2.50	4.17
	Test 2.2 Description: Position groups of 3 or 4 markers from Group A at an angle of 20° have observers	
	indicate the distance at which light is visible and rate the visibility as above.	
	Average score for all observers must be 2.00 or better with no more than 25% of the observations from less than 150 m.	2.56
4.0	**Strength test and pull-off tests**	
	These tests are not required due to limited direct exposure to vehicles.	

APPENDIX E: SOLAR-POWERED RAISED PAVEMENT MARKER OBSERVATION TEST RECORDING FORM

Test 3.2.1																
Each marker is to be viewed individually from 200 meters. View each marker when displayed and enter a score.																
5=excellent visibility; 4=good visibility; 3=fair visibility; 2=visible but not recommended for installation;1=not visible.																
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Group A																
Group B																
Test 3.2.2																
Each marker is to be viewed individually from 200 meters. View each marker when displayed and enter a score of 1-5, as above.																
Group A																
	15	**13**	**11**	**7**	**5**	**3**	**1**									
White																
	16	**14**	**12**	**10**	**9**	**8**	**6**	**4**	**2**							
Amber																
Group B																
	15	**13**	**11**	**7**	**5**	**3**	**1**									
White																
	16	**14**	**12**	**10**	**9**	**8**	**6**	**4**	**2**							
Amber																
Test 3.2.3																
Markers will be viewed in groups of 3-4 markers at a time. For each marker, enter the distance, in meters, at which you can first see light.																
	1		**3**		**5**											
White																
	7		**11**		**13**		**15**									
White																
	2		**4**		**6**					**8**		**9**		**10**		
Amber							**Amber**									
	12		**14**		**16**											
Amber																