TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.: TX-90/1151-1F

2. Government Accession No.:

3. Recipient's Catalog No.:

4. Title and Subtitle: Raised Pavement Marker Reflectivity

5. Report Date: November 1990

6. Performing Organization Code:

7. Author(s): V.J. Pezoldt, R.J. Koppa, R.A. Zimmer, A.T. Perry and H.W. Milsap

8. Performing Organization Report No.:

9. Performing Organization Name and Address:
Texas Transportation Institute
The Texas A&M University System
College Station, TX 77843-3135

10. Work Unit No.:

11. Contract or Grant No.: 2-10-88/9-1151

12. Sponsoring Agency Name and Address:
TX State Department of Highways & Public Transportation
Transportation Planning Division
P.O. Box 5051
Austin, TX 78763

13. Type of Report and Period Covered:

14. Sponsoring Agency Code:

15. Supplementary Notes:
Research performed for the State of Texas.

16. Abstract

In recent years, problems associated with retaining retro-reflective raised pavement markers (RPMs) on Texas highways have to a large extent been successfully resolved. Problems with the maintenance of acceptable levels of RPM reflectivity, on the other hand, have remained persistent. This report summarizes a variety of activities, including determination of minimum effective retroreflector performance in terms of visual detection thresholds, field and laboratory studies of the durability of RPM reflectivity, and research and testing associated with the development of a field measurement device, that address the RPM reflectivity and visibility issue.

Tabled values of specific intensity (SI) are provided at which RPM replacement should be considered for various conditions of weather, sight distance, and opposing traffic. Studies of RPMs subjected to thermal stress and abrasion suggest glass-faced RPMs better retain SI than comparable acrylic-faced markers. A prototype vehicle-mounted infrared device for evaluating installed RPMs was developed and is described. Changes in the SDHPT RPM purchasing and testing procedures are recommended for consideration.

17. Key Words: Raised pavement markers, reflectivity, visual thresholds, photometry

18. Distribution Statement: No restrictions. This document is available to the public through the National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

19. Security Classif. (of this report): Unclassified

20. Security Classif. (of this page): Unclassified

21. No. of Pages: 117

22. Price:

Form DOT F 1700.7 (8-69)

RAISED PAVEMENT MARKER REFLECTIVITY

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Research Report 1151-F
Study Number 2-10-88/9-1151

Sponsored by

Texas State Department of Highways and Public Transportation

September 1990

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	centimetressquared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

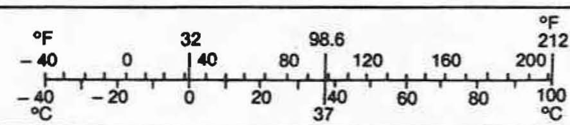
NOTE: Volumes greater than 1000 L shall be shown in m^3.

		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

ABSTRACT

In recent years, problems associated with retaining retroreflective raised pavement markers (RPMs) on Texas highways have to a large extent been successfully resolved. Problems with the maintenance of acceptable levels of RPM reflectivity, on the other hand, have remained persistent. This report summarizes a variety of activities, including determination of minimum effective retroreflector performance in terms of visual detection thresholds, field and laboratory studies of the durability of RPM reflectivity, and research and testing associated with the development of a field measurement device, that address the RPM reflectivity and visibility issue.

Tabled values of specific intensity (SI) are provided at which RPM replacement should be considered for various conditions of weather, sight distance, and opposing traffic. Studies of RPMs subjected to thermal stress and abrasion suggest glass-faced RPMs better retain SI than comparable acrylic-faced markers. A prototype vehicle-mounted infrared device for evaluating installed RPMs was developed and is described. Changes in the SDHPT RPM purchasing and testing procedures are recommended for consideration.

DISCLAIMER

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1. INTRODUCTION

Background of Project

Literally millions of raised pavement markers (RPMs) have been installed on Texas highways. These markers are intended to provide assistance to motorists by delineating lanes and intersections and providing other guidance information where painted lines may not be effective, especially on wet pavements and under other adverse conditions. In order for RPMs to effectively and efficiently fulfill this positive guidance function, two obvious but important conditions must be met:

1. A significant proportion of the markers must be retained on the roadway, and

2. A minimally acceptable degree of retroreflectivity must be maintained.

Marker retention problems have to a large extent been successfully resolved. At one time premature failure of the adhesive material and/or pavement failure beneath the RPMs was commonplace on asphalt concrete pavements. The introduction and increased use of improved methods and materials, notably "bitumen," have made the marker retention problem much more manageable (Tielking & Noel, 1988). Problems with the maintenance of acceptable levels of RPM reflectivity, on the other hand, have remained persistent.

Cooperative Research Project 2-18-82-322, "A Study of Raised Reflective Pavement Markers," both contributed to the advances in marker retention performance and made some important initial evaluations of the loss of reflectivity with time and exposure to traffic. As part of that study estimates were made of minimum levels of luminous intensity and minimum marker density that provide adequate path delineation. These estimates were based on judgments of photographic representations of RPMs by a panel of traffic engineering experts. The present project was undertaken to assist the SDHPT in efforts to increase the effective reflective life of RPMs. Ideally the useful life of RPMs would be comparable to their pavement life. In addition, this effort was intended to provide recommendations that will assist the department in objectively determining when RPM replacement is warranted based on insufficient reflectivity.

Project Objectives

As defined in the initial statement of work, the primary objectives of the present project were to:

1. Determine minimum effective retroreflector performance in terms of visual detection thresholds under nighttime and simulated wet pavement conditions with representative drivers;

2. Identify possible alternative approaches to fabricating and bonding retroreflective elements so as to assure SDHPT does not have unrealistic requirements for effective retro-reflective pavement marking devices;

3. Develop a cost-effective method of evaluating marker retroreflectivity on the highway; and

4. As necessary, develop changes to existing SDHPT Specifications and Test Methods to incorporate the findings of this study.

As the project evolved, additional tasks and objectives were identified. These included:

5. Investigations of the relative durability of different types of RPMs when exposed to vehicle traffic and to extremes of temperature;

6. A preliminary study of the feasibility of restoring degraded RPMs to useful service; and

7. Determination of practices regarding RPM use in jurisdictions outside of Texas.

The approach to meeting these objectives entailed a variety of activities involving field and laboratory studies of RPM reflectivity and durability, research, development and testing associated with developing a field measurement device, and contact with highway department personnel in Texas and other States to determine the experience and practice with RPMs in various jurisdictions.

Organization of the Report

The remaining sections of this report emphasize specific facets of the overall project.

Section 2 provides a brief discussion of the photometric methods used for measuring the reflectivity of RPMs. Particular emphasis is placed on differences in the measurement techniques employed in the TTI laboratory and those used in the SDHPT lab.

Section 3 describes the development of a mobile RPM measurement system.

A series of empirical studies and analytic efforts aimed at determining threshold levels of RPM reflectivity among the driving population are presented in Section 4. These studies were directed at answering the question, "How bright is bright enough?"

Section 5 addresses the issue of RPM durability. Included in this section is a brief discussion of the materials used in RPM fabrication, a photometric assessment of RPMs removed from service on Texas highways and descriptions of a series of tests of the influence of thermal stress and abrasion due to automobile tire impacts on RPM reflectivity.

The feasibility of restoring the reflectivity of damaged RPMs is discussed in Section 6.

Section 7 provides a summary of experience and practices regarding RPM use in several jurisdictions outside of Texas.

The final part of the report, Section 8, summarizes conclusions and recommendations arising from all of the project efforts.

Table 1-1 is provided to assist the reader in locating information specific to each of the stated objectives and project activities.

Table 1-1. Guide to locating specific project information.

Project Objective/Task	Report Section and/or Page
1. RPM detection thresholds	Section 4 & pages 101, 103
2. Alternative approaches to RPM bonding and fabrication	Pages 61-63
3. On-highway RPM evaluation	Section 3 & pages 101, 103, 104
4. Changes to RPM specifications and test methods	Section 2 & pages 101, 104
5. RPM durability	Section 5 & pages 102-103, 104
6. Restoring RPM reflectivity	Section 6 & page 103
7. RPM experience and practice outside Texas	Section 7 & page 103

2. PHOTOMETRIC ASSESSMENT OF RAISED PAVEMENT MARKERS

TTI Laboratory Measurement

Laboratory measurements for this project were conducted in accordance with a procedure adapted from Society of Automotive Engineers Standard SAE J594f - Reflex Reflectors which is in turn a simplified version of the American Society for Testing and Materials (ASTM) Standard Practice for Measuring Photometric Characteristics of Retroreflectors, Designation E 809-81. A description of the photometric laboratory established for these measurements at the Texas A&M Riverside Campus and the procedure used to evaluate RPMs is provided in Appendix A.

Measurement of the photometric performance of RPMs is based on the ratio of the luminous intensity of the retroreflector to the luminous intensity incident on the reflector. This relationship is called specific intensity (SI) and is defined as:

$$SI = ED^2/E_n$$

where

E = Illuminance at the observation position.
D = Distance between the center of the photoreceptor entrance aperture and the reference center.
E_n = Normal illuminance at the retroreflector.

In the English system of units, SI is expressed in candela per foot-candle. In the CIE vocabulary, this relationship is called the coefficient of luminous intensity (CIL) and is expressed in metric units as candela per lux.

Photometric Assessment at SDHPT

Photometric assessment of RPMs conducted by D-9 of the SDHPT are conducted in accordance with SDHPT Method Tex-842-B, Method for Measuring Retroreflectivity. This test method, like the method employed in the TTI laboratory, is a variant on ASTM Method E809-81. Significant differences between the SDHPT and TTI test procedures, however, warranted an investigation to determine the comparability of results obtained in the two laboratories and a determination of the reasons for any differences in measurements that might be accounted for by the different procedures. To that end, a small sample of RPMs measured in the TTI lab was sent to the D-9 lab for independent assessment. Table 2-1 provides the specific intensities of 6 RPM reflective surfaces as measured by the two facilities.

Inspection of Table 2-1 indicates a substantial difference in the results obtained from the two labs. We believe the explanation for these differences lies in the differences between the two test procedures used.

Table 2-1. Comparison of RPM photometric assessment by the SDHPT and TTI laboratories.

Specimen	D-9	TTI
1A	3.00	0.95
1B	0.32	0.14
2A	9.80	3.43
2B	1.60	0.85
3A	1.70	0.67
3B	6.80	2.24

All measurements were made at a diversion angle of 0.2 degree and an entrance angle of 4 degrees.

The SDHPT formula for finding the specific intensity (SI) of a test specimen is:

$$SI = D^2/K_i \times R/R_{std}$$

Where

D = the distance from the light source to the specimen.
K_i = the ratio of the incident light (in ft-c) on the standard specimen divided by the measured luminance (in ft-L) of that standard.
R = the luminance of test specimen - ambient luminance without specimen.
R_{std} = luminance of standard specimen.

The sensor used by D-9 with the Tektronix J16 photometer is the J6503 luminance probe (8 degree cone). This probe is mounted on a board with a sliding track that allows the instrument to be moved laterally with respect to the returning beam from the test specimen, so that the divergence angle can be varied. The probe is pointed at a small mirror set at 45 degrees for the sake of convenience in mounting. The specimen is mounted at 90 degrees from its usual horizontal orientation, and the transit head moves in azimuth to change the angle of incidence (or entrance angle, as the SDHPT procedure terms it). This setup appears to have been designed primarily to handle larger signs or reflective surfaces, and to have been adapted for measuring the retroreflectivity of raised pavement markers or other similar small reflectors. This explains, we believe, why the SDHPT uses a luminance probe, suitable for measuring the brightness of an extended source of light, rather than the more customary illuminance probe available for the J16 photometer.

To align this setup, the transit head specimen holder accepts a small plane mirror. The incident angle is set to zero. The mirror is rotated to assure that there is no misalignment, and then the beam of light reflected by this mirror is adjusted by rotating the transit head in azimuth until it frames the projector lens squarely in the middle. This sets up an incident angle of zero. If the beam is off in elevation, the transit head can be changed using the leveling adjustments to correct for this error. The alignment mirror is then removed.

The mirror is replaced with a retroreflector which is a 3-inch diameter disk. The disk holder incorporates a small motor which spins the reflector in the plane normal to the incident beam of light at a rapid rate. The Test Method calls for 300 rpm, but the Test Engineer said that the rate of rotation was 50 rpm. The purpose of spinning this calibration or "standard" retroreflector is to obtain an average value of luminance over its surface. It should be noted that the luminance probe is positioned at the divergence angle of 0.2 degree. At the distance of 50 feet, the standard subtends only 0.286 degrees of arc, versus the field of the instrument, which is 8 degrees. The luminance probe averages over the entire field of view to provide the reading in foot-lamberts. This reading is then repeated with the standard retroreflector removed, but the holder spinning, to record background luminance. The latter reading is subtracted from the former reading to provide the luminance of the standard:

$$R_{std}$$

The retroreflector is placed in the specimen holder. The transit head is moved in azimuth to the setting desired for incident angle, and the luminance probe is moved toward or away from the lens of the projector, and, it follows, the returning beam from the specimen to set the divergence angle. The luminance of the specimen is recorded, and then the luminance of the setup with the specimen removed is subtracted from this reading. This net value is:

$$R$$

Thus, the luminance of the 8 degree field with the test specimen in it is divided by the luminance of the same field with a standard reflector in it. With this approach, it is unnecessary to measure the amount of incident light falling on the specimen (illuminance of the source). Since the reflectance of the standard is known, and the illuminance is the same for both the test specimen and the standard, their ratio is directly related to the reflectivity of the test specimen.

Evidently, the ratio K_i was computed from measurements that were made when the standard specimen was first adopted. Since the illuminance which is in the numerator gives rise to the luminance that is in the denominator, as long as the reflectance of the specimen does not change, this ratio should not vary.

The SDHPT formula may be rationalized as follows:

$$SI = \frac{\text{sq ft x ft-Lamberts}}{\text{(ft-candles/ft-1) x ft-Lamberts}}$$

these units cancel to yield:

$$SI = \frac{\text{sq ft x ft-lamberts}}{\text{ft-candles}}$$

but luminance L = ft-lamberts = $(1/\pi)$ candela/sq ft

$$\text{then, } SI = \frac{\text{candela}}{\text{ft-candles x } \pi}$$

Specific intensities obtained using an illuminance probe (J6511) per the ASTM/SAE methods reduces to:

$$SI = \frac{\text{candela}}{\text{Ft-c}}$$

Therefore, it appears that the SI values obtained by the SDHPT method should differ from those obtained in the TTI laboratory by a factor of π.

Table 2-2 replicates Table 2-1 with addition of a third column; the D-9 SI values divided by π. Inspection of Table 2-2 reveals the excellent agreement of the two independent measures, differing by a factor of π. The only exception is JU2B, which must be either an incorrect measurement by D-9 or by TTI. Thus any measurements made by the D-9 laboratory can be converted to its equivalent SAE or ASTM SI by dividing by π. The D-9 laboratory, it will be remembered, uses an 8 degree luminance probe as a sensor, as compared to the illuminance probe specified in ASTM/SAE and used

Table 2-2. Comparison of RPM photometric assessment by the SDHPT and TTI laboratories with adjustment to D-9 values.

Specimen	D-9	TTI	D-9/π
1A	3.00	0.95	0.96
1B	0.32	0.14	0.10
2A	9.80	3.43	3.12
2B	1.60	0.85	0.51
3A	1.70	0.67	0.54
3B	6.80	2.24	2.17

by TTI. This difference in probes must account for this constant difference in SI between the two laboratories.

Changes to Existing Standards and Specifications

The fundamental or top-level specification for RPMs is Item 674 in the 1982 Standard Specifications for Construction of Highways, Streets, and Bridges (SDHPT, 1982). This section, entitled "Pavement Markers (Reflectorized)," provides definitions and classifications for the devices, and refers the user to Specification D-9-4200 and in a general call-out (674.5) to the Manual of Testing Procedures for guidance on the visibility aspects of RPMs.

D-9-4200 is the definitive material specification for RPMs. It repeats the classification scheme of Item 674, adds some details on the geometry of markers and shell characteristics, and refers to Test Method Tex-842-B (discussed above) for evaluating specific intensity.

The results of this research do not indicate that any changes need be made to Item 674 in the Department Standard Specifications. D-9-4200, under Section V, Paragraph D, lists specific intensities for RPMs that must be based on measurements made with the ASTM or SAE method, which, as discussed above, differ by a factor of pi (3.1416) from values obtained using Tex-842-B. The values in D-9-4200 are thus very conservative (low) for new devices. Consideration should be given to revising these values upward by a factor of pi, if Tex-842-B is not revised.

The Department should consider replacing Tex-842-B with ASTM E 809-81, Standard Practice for Measuring Photometric Characteristics of Retroreflectors in order to provide values of SI that can be readily reproduced in any photometric laboratory. This replacement could be accomplished by direct call-out of ASTM E 809-81 in D-9-4200, rather than Tex-842-B, or by revising Tex-842-B to merely reference the ASTM practice. Alternatively, the Department could adopt SAE J594f Reflex Reflectors with minor clarifications for applicability to RPMs. The ASTM Standard Practice is possibly more complicated than is really necessary for the purposes of quality control, but could be readily simplified.

Field Measurement

One of the objectives of the project was to develop a cost-effective method of evaluating RPM retroreflectivity on the highway. The results of this development effort are discussed in Section 3. On-pavement measurements of RPM specific intensity needed for the various experimental studies described in the following sections were made using prototypes of the field measurement device developed.

3. DEVELOPMENT OF A MOBILE RAISED PAVEMENT MARKER MEASUREMENT SYSTEM

Introduction

The effectiveness of a raised pavement marker to delineate the roadway is based on its level of retroreflection. Retroreflection is the ability of a device to return light in directions close to that from which it came; in this case from automobile headlights back to the drivers eyes. As discussed in Section 2, several laboratory practices for the measurement of retroreflectivity have been developed. These laboratory methods (e.g. ASTM E 809, SAE J594F, Tex 842-B) specify very stringent measures to be taken when conducting the tests. Even with painstaking efforts to maintain specified distances, placement, angles and equipment calibration, the test/retest reliability of these tests is on the order of 90%-95%

The task reported here investigated the feasibility of performing photometric measurements of installed RPMs that are comparable to laboratory based measures. This would be accomplished from a moving vehicle, 30 to 55 MPH, in either the dark or daylight. The system would be self contained and operate from basically any type of highway vehicle; i.e., a passenger car or truck. Ideally it would require only one operator who would also drive the vehicle. The system would contain an unattended recording device so as not to interfere with the operation of the vehicle.

Design Requirements

In order to move the measurements out of the laboratory and on to the highway, a number of obstacles had to be overcome. The first was that laboratory measurements are taken in a darkened room. In the lab, even the small amount of ambient light is accounted for in the calculation of specific intensity. Because this technique was not possible on the highway, a method needed to be developed that would either eliminate the low levels of ambient light found in night testing or that would use a type of illumination and hence reflection that was not found in normal day or night ambient light.

Once a suitable method of static measurement was decided upon, the problem of motion was addressed. This problem reduces to one of speed of operation of the measurement system since a target RPM is available for measurement for only a very short time. For example, if the longitudinal measurement area projected on the pavement was 8 inches and the vehicle was moving at 50 MPH, a marker would be in a favorable position for approximately 9 thousandths of a second. This speed requires a very fast and stable light measurement method because the level changes from basically zero to a high level. If the measurement system is too slow, it will not capture the maximum level. If the system is fast but underdamped, the value will be spuriously high. Because the "true" light value is only present for a brief instant, a method of holding or memorizing the reading must be incorporated to allow time for recording. Once the value is recorded, the memory must be cleared and made ready for the next reading.

Another requirement is that the system must recognize when an RPM is in favorable position to be measured. This detection is needed to activate the process of peak measurement, storage, recording and resetting for the next measurement. The detection phase is problematic since the condition of RPMs on the roadway is highly variable. RPMs that are in good shape and are functional present little difficulty. Units that have failed or provide very little retroreflection present a problem since they may appear as non-retroreflective ceramic bumps. For this reason a lower limit for the RPM detection circuit was set at about 0.1 SI. Below this limit, the system would produce false triggers on glass beaded paint stripes.

Video System

To meet the above criteria, a prototype system was designed and developed that used a high intensity light source to illuminate the RPM and a monochrome video camera to measure the retroreflectance. The basics of this system are shown in Figure 3-1. In order to keep the observation angle to a minimum, a 50% transmission mirror was used to pass the light source and to reflect the returned light from the RPM into the camera along the same axis. In order to provide a constant reference level, an RPM with a known laboratory measured specific intensity was placed in the field of view along with the target RPM. These two images were then electronically split and processed into two separate but identical circuits. Each half of the frame was sampled 30 times a second, and the intensity or luminance was integrated for each sample. The peak integrated value from each RPM was held in analog memory as long as the test RPM was in the field of the Infrared Detector. The output of the peak value circuits was connected to an Analog Divider to provide a percentage output. The percentage was that of the test marker relative to the reference marker, which was set at 100%. As the test RPM left the field of the detector the Cycle Timer instructed the Meter and Printer to record the value. Once the value was recorded, the peak reading circuits were reset to zero for the next readings.

A prototype of the system was constructed using both equipment on hand at TTI and project hardware. Shop tests of the system showed that if the camera aperture was closed down and the automatic gain controls disabled, ambient room light had no effect on the measurement. The reference RPM selected was the same type as the target marker with a known high SI value. Numerous tests were conducted in the shop, both to determine the accuracy of the

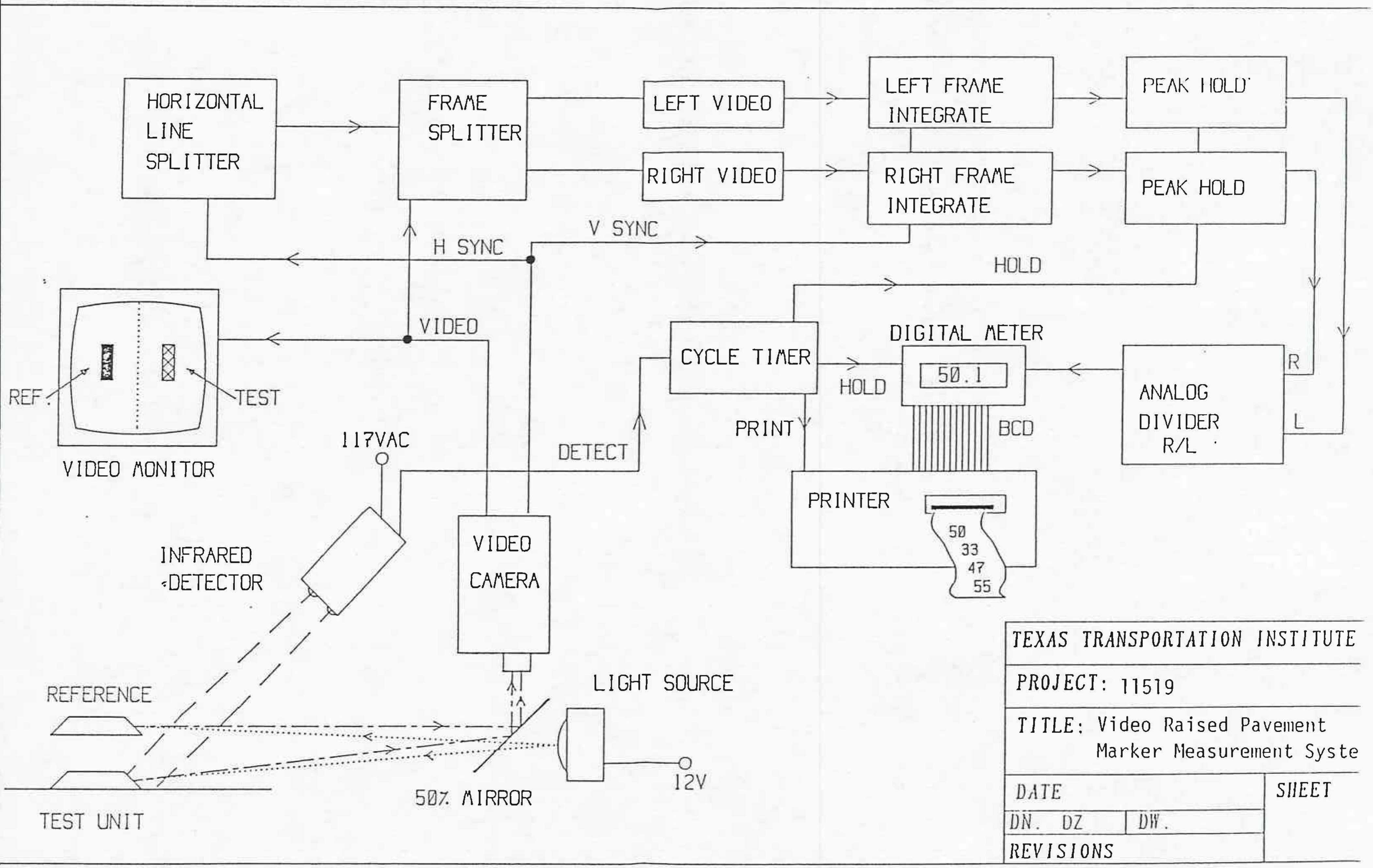

Figure 3-1. Video-based field measurement system

system and to identify any problems. The static reliability proved to be very good, within 1% to 2% repeatability. Accuracy was also good. Specific intensity measures of target RPMs were within about 5% of laboratory measurements.

Changes in the intensity of the high intensity driving light that served as the light source were not critical since the target RPM was always compared to the reference RPM in the same field of view. As long as the same intensity of light fell on both the target and reference RPMs, differences in the absolute intensity from one target to the next did not influence the accuracy of the measurement. More problematic, however, was assuring that the target and reference RPMs were in fact receiving equivalent light intensities. Because the source produced light that varied considerably in intensity within a few inches laterally, aiming the entire system proved very difficult.

Further development of the video-based system required both resolution of the aiming problem and the use of a more sophisticated video camera system than was obtainable within the resources of the project. Therefore, a simpler approach based on a modulated infrared beam was pursued.

Infrared Modulated Beam System

While working with the video system, it was observed that the Infrared Detector, used in that system only to sense the presence of an RPM, had potential for providing analog values. The unit is commercially built by the Tandy Corporation as an intrusion detector. It contains both an infrared (IR) transmitter and receiver with associated optics. The transmitted beam is modulated or switched on and off at a rate of 10 kHz. This allows the received signal to filter out all but the 10 kHz information which has been reflected. This technique results in a signal that is insensitive to steady state ambient light or 60 Hz room lights. When operated in direct sunlight, however, the IR content is so high that it overloads the receiver, causing false readings.

A block diagram of the prototype system based on the IR unit is shown in Figure 3-2. The vehicle battery powers the IR unit directly and is converted to 115 VAC to power the remainder of the circuitry. The Tandy unit has been slightly modified to allow the raw received signal to feed the prototype computation circuits developed for the project.

The modulated IR light is reflected from a target RPM at a distance of about 12 feet. The received light is converted to an AC voltage in the receiver where it is fed to the computation unit. The incoming signal is split and is sent to the **RPM Detect** circuit and to the **Data Filter.** The Detect circuit acts like a switch; when an RPM is in the beam, it instructs the other components that a measurement is required. The data is first filtered to remove

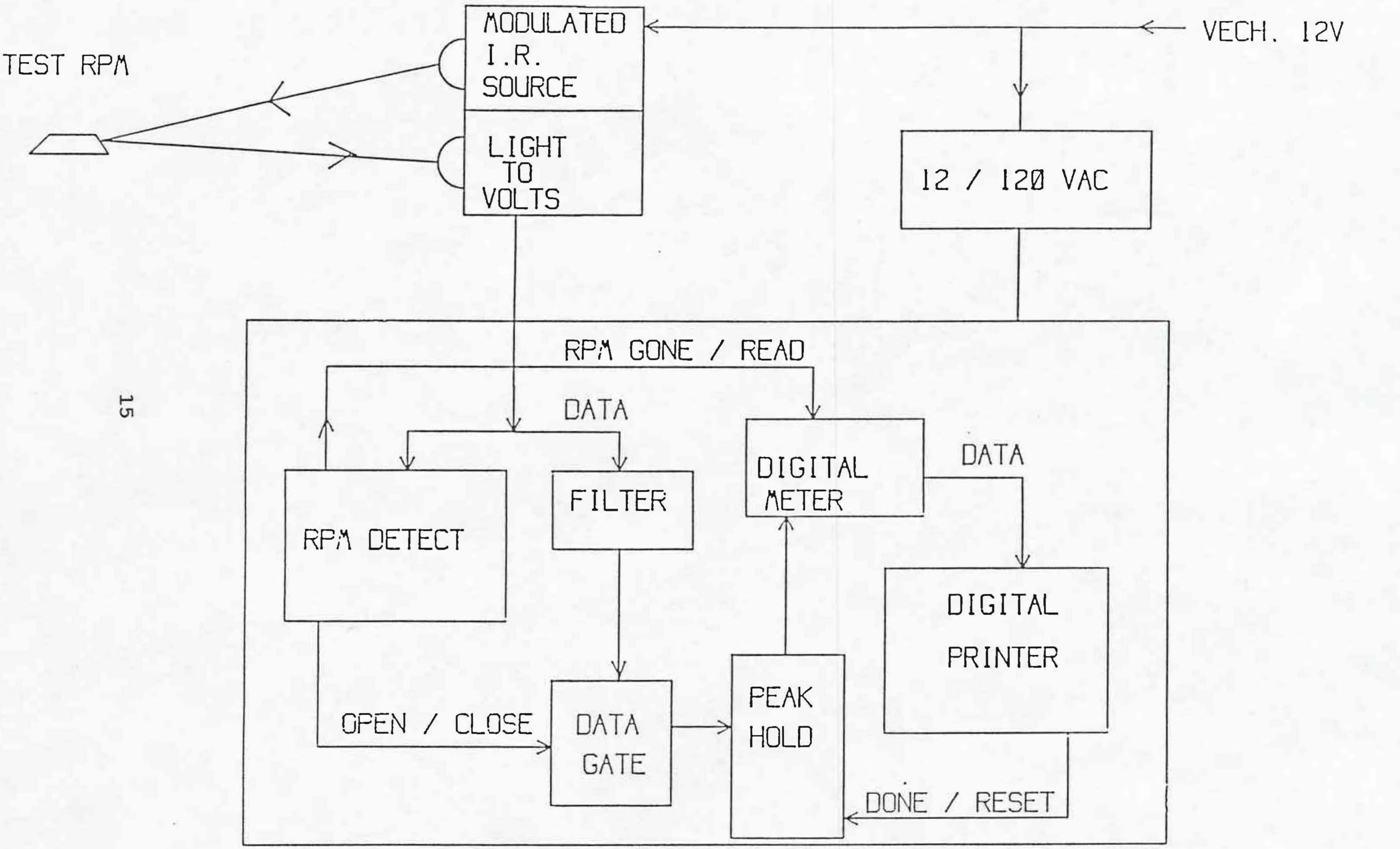

Figure 3-2. Block diagram of prototype infrared field measurement device

any ambient light signals. It is then gated or switched into the **Peak Value Holding** circuit. As long as an RPM is detected in the beam, the peak reflected value during that time is held in analog memory by this circuit. When the RPM Detect circuit senses that the RPM has passed, it sends a signal to the **Digital Meter** to convert the peak signal level to numeric digits and display them on the front panel. Once the digits are available, they are sent to the **Digital Printer** to record the reading. To assist the driver in operation, a beeper was installed and connected to the RPM Detect circuit. Each time an RPM is in the field of view of the sensor, a tone will sound if the beeper is enabled.

The unit is installed under the bumper of a car or truck as illustrated in Figure 3-3. It is then aimed at an RPM of known specific intensity approximately 12 feet forward. By alternately uncovering and covering the RPM, SI values are displayed on the panel meter. The units gain control is then adjusted to produce the correct reading. After this adjustment, the unit is ready for automatic operation. The system has been found to operate well in most light conditions except full sunlight.

RPMs measured with this system in the shop show very good agreement, less than 5% disparity, with the values obtained in the laboratory. This is in normal room light at a distance of about 12 feet. Field tests at the Riverside Campus Proving Grounds indicated that measurement speed did not seem to be a factor with runs made up to 55 MPH. A problem encountered with this system, as with the video system, is aiming while traveling at highway speeds. Static tests showed that lateral alignment within an inch or two affected the reading by less than 5% to 10%, but trying to hold this tolerance at road speed is quite difficult. In an attempt to devise a feedback system, the sensor was aligned with the center of the wheels on the left side of the vehicle. If the driver feels the wheel going over the RPM, he can be confident that the aiming is fairly close.

Even with this aiming technique, lateral positioning cannot be maintained within the few required inches for each RPM in a string. If a set of RPMs to be measured are fairly homogeneous, the aiming problem could be treated statistically; averaging the measured SI of multiple RPMs to provide a single data point. This would not, however, allow detection of individual low SI RPMs. Alternatively, multiple measurements of each target RPM could be made. The number of measurements and a criterion for acceptable variability among the multiple measures would need to be established for this scenario to prove practical.

Another observation made while testing the device was that the detect level must be set at about 0.09 SI to avoid activation by objects other than the RPMs. At this level, RPMs that are very degraded will fail to trigger the detect or measurement circuits. This condition must be carefully analyzed by the operator so that

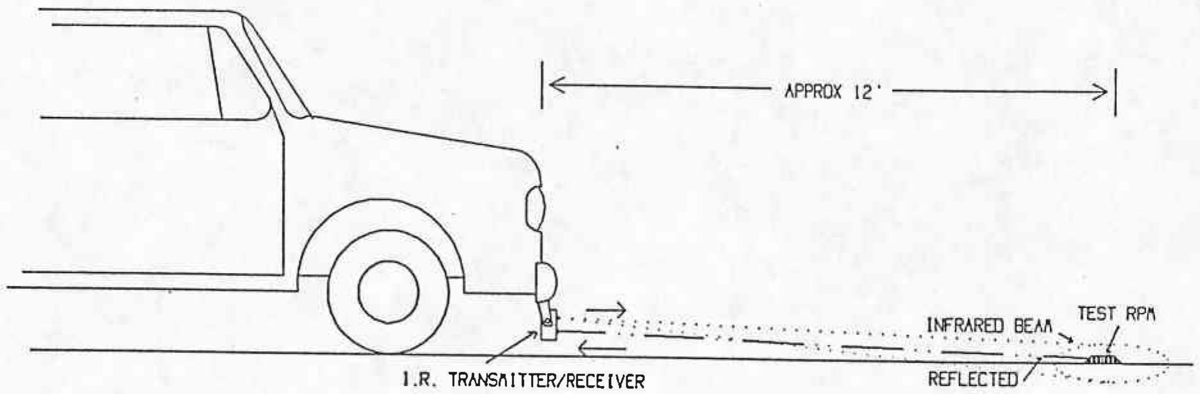

Figure 3-3. Configuration of installed infrared field measurement device.

he or she is certain that failure to detect the RPMs is due to their low reflectivity and not to improper aiming.

The schematic diagram of the Mobile IR system is shown in Figures 3-4 and 3-5.

System Costs and Cost Effectiveness

Since this project produced only one prototype system, the cost of commercially producing the units cannot be determined accurately at this time. Estimates can be made, however, based on the current price of the components used in the prototype and estimates of costs for producing the circuit boards.

The most expensive components of the system are the digital printer and readout, which total about $1600 in small quantities. The remainder of the components; infrared detector, power supply, circuit board, case and controls, can be purchased for approximately $600. Fabrication of one unit at a time would be costly, with the price dropping significantly with quantity production. The single unit labor cost at this time would be about $1,000. Thus, built one unit at a time, the infrared field measurement system as currently configured would cost approximately $3,200 per unit. This cost estimate would increase to the extent that additional hardware may be required to improve the aiming capability of the system.

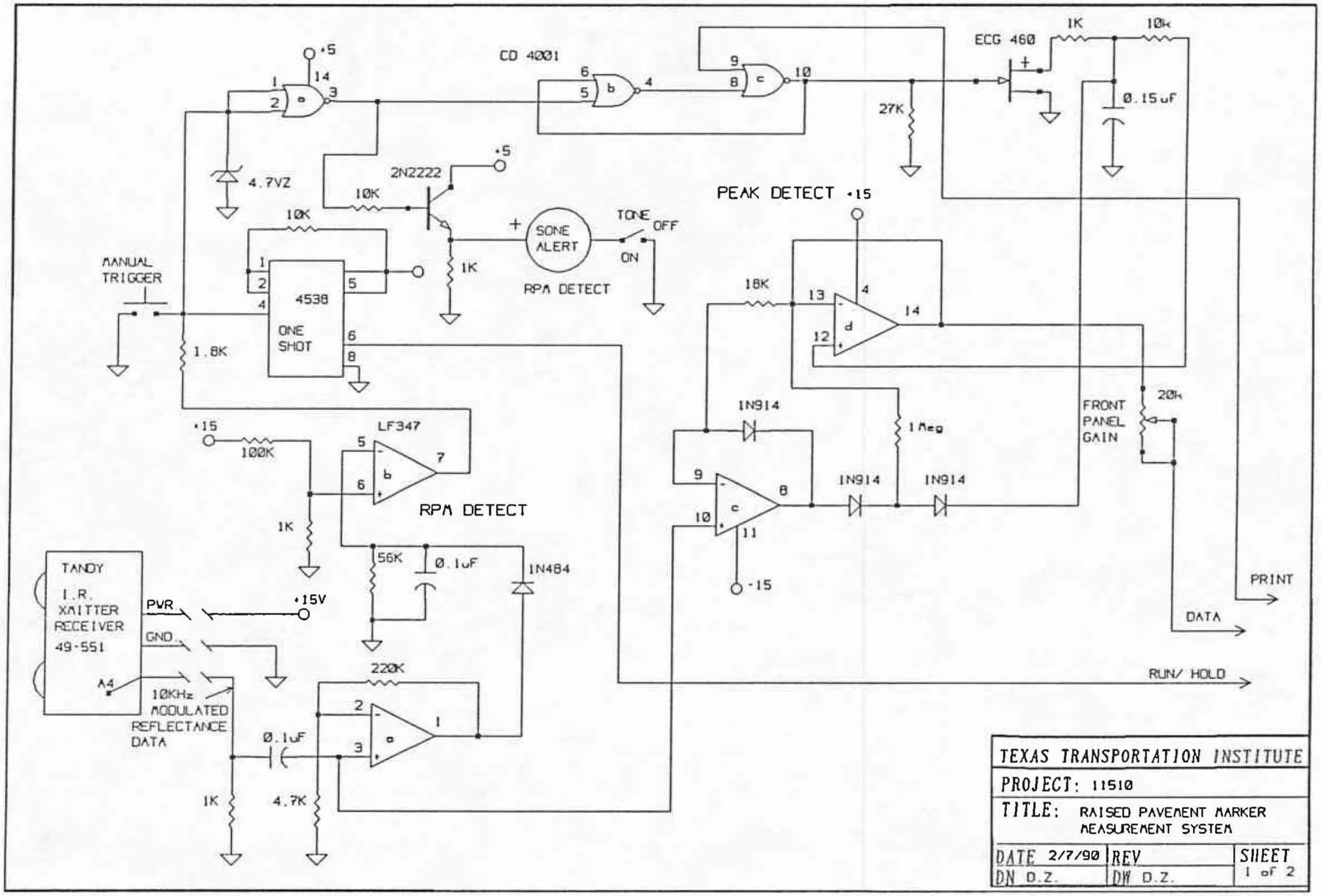

Figure 3-4. Schematic of infrared field measuring device (1).

DM-4100D INTERFACE WITH DPP-Q7 THERMAL PRINTER

The DM-4100D may be connected directly to Datel-Intersil's DPP-Q7 Miniature Printer to form a functional data logger. The required connections are shown below.

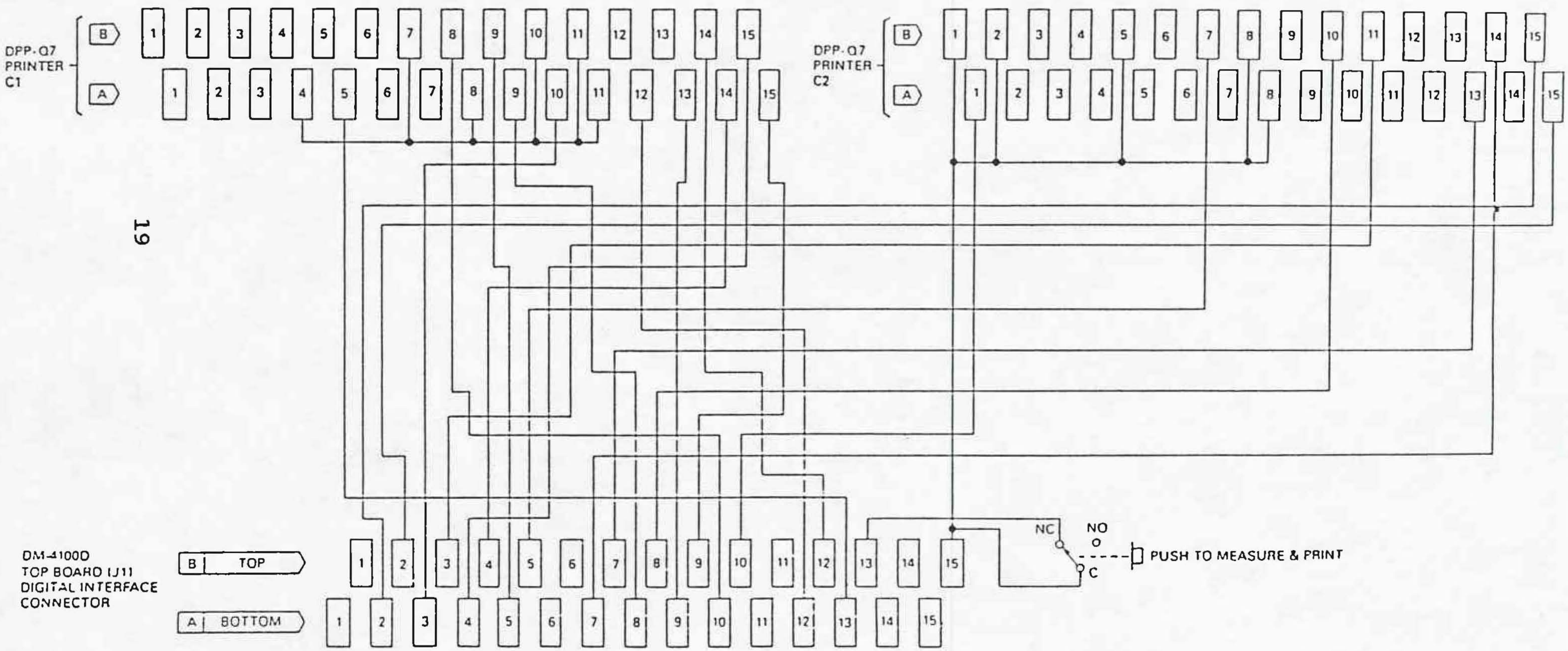

Figure 3-5. Schematic of infrared mobile field measurement device (2).

No formal determination of the cost effectiveness of using the system was undertaken for this project. Factors which would need to be considered in determining the cost effectiveness of the system include the initial training costs for personnel to operate and maintain the system. Although the system is generally easy to use, the extent of training necessary for proper application is directly related to improvements needed in the system's aiming capability. Because the system can be installed on any passenger vehicle or truck, no special vehicle costs would be incurred beyond those associated with vehicle mileage accrued during RPM measurement.

The potential benefits to be realized from use of the system arise from sources which are difficult to quantify because they depend on the extent to which RPMs are used and the existing RPM replacement practices in each SDHPT district. If RPMs are routinely being replaced on the basis of very conservative subjective judgements regarding RPM brightness, then use of a system which allows an objective measure of RPM specific intensity could reap substantial savings in unnecessary replacement costs. Conversely, in situations where RPMs are allowed to remain well beyond their useful life, implementation of a replacement schedule tied to measured specific intensity might result in increased RPM expenditures. This potential expense must be balanced against the judged benefit resulting from the enhanced path guidance provided by acceptably bright RPMs.

Conclusions

The video system used in the first prototype produced very good results when used in a static or stationary mode. In motion, errors were introduced due to lag or poor response of the video camera used. This technique is not recommended unless a very high speed, high quality camera specific to this application is used. The light sources on this system were also deficient in that they did not produce an even light level across the area of interest at a high enough illumination.

The second design was based on a modulated infrared beam of light reflecting from the target RPM back to an IR receiver. This technique uses some hardware and techniques of the first method but is much simpler. The sensor mounts under the front bumper with a small cable leading to the control unit in the front seat. This method will work in all ambient light conditions, except full sun, due to the modulated beam. RPM measurements with this system under room light static condition are very comparable to those obtained in a completely dark test chamber using a Tektronix J16 photometer.

A problem in using the IR system that may need further work is the degree of accuracy required by the driver to aim the sensor at the test RPMs at highway speeds. This condition may be greatly improved by measuring a string of homogeneous RPMs or by making multiple passes of each RPM to be measured and applying statistical techniques.

An easy-to-use manual for both District maintenance personnel and traffic engineers should be prepared. Such a manual should provide detailed operational instructions for the Infrared Field Measurement System and simple algorithms for any sampling or statistical techniques that need to be applied to evaluate the condition of installed raised pavement markers.

4. THRESHOLD STUDIES

A series of empirical and analytic studies were conducted to determine the lower threshold of RPM specific intensity for a sample of Texas drivers. Determination of such thresholds provides a means to establish the minimum level of RPM reflectivity which can provide path information for motorists.

Threshold Study 1: Threshold Specific Intensities of Retro-reflective Raised Pavement Markers

Purpose and Objectives

The purpose of this test was to establish the lowest practicable values of specific intensity (SI) at which RPMs are discriminable from backgrounds under two operational conditions: (1) minimum light levels with no competing sources and (2) higher light levels with competing sources. The former condition simulates a dark rural highway with no extraneous sources of light or oncoming traffic. The latter condition simulates an urban situation with advertising signs and other lighted objects on or near the roadway. The objective was to determine, under both of these conditions, how much residual SI must be present for a driver to unequivocally say that the object on the roadway that he or she sees is an RPM.

A secondary objective was to demonstrate the equivalence of loss of transmission of light through the optics of the RPM with loss of effective area of the RPM. Perceived brightness of these objects is based on the total number of lumens reaching the eye. Below a critical source diameter of 1 minute of visual arc, the source is perceived as a point of light, like a star. In this situation, reduction in the physical size of the object is seen as a reduction in brightness.

Ground Rules and Assumptions

1. Middle-aged and older drivers have inherently inferior contrast sensitivity and detection thresholds as compared to younger drivers. RPM's that are identifiable as such to a sample of drivers from the older population will pose no problem to younger drivers.

2. The arrangement of RPM's in patterns that conform to roadway geometry provide extra cues for identification.

3. The simulated urban environment should be as realistic, but cannot encompass all operational situations or be deemed "typical."

Test Site Description

Test RPMs

Pilot tests established that SI values of 4 x 4 inch raised pavement markers that are less than about 7 per cent of the original SI still are reliably detected by an observer under perfect seeing conditions. Anything above 50 per cent of nominal new value will be unmistakable under nearly any seeing condition. The specific intensities of the specimens prepared for use in this study, therefore, were very low compared to new RPMs. The SI values (candela/incident ft-candle) of the test specimens are indicated in Table 4-1. The SI's reported in the table were measured at 0 degrees entrance angle and 0.2 degree observation angle. SI changes very little with small amounts of observation angle (i.e., the angle between the observer's eyes and the source of illumination). The degradation in retroreflectivity of the test RPMs was produced by abrading the reflective surfaces with emery cloth.

Table 4-1. Specific Intensity of threshold study RPM specimens.

Color:	Clear	Amber	Red
	0.007	0.005	0.002
	0.051	0.013	0.030
	0.068	0.015	0.051
	0.080	0.065	0.068
	0.120	0.123	0.090
	0.188	0.134	0.161
Nominal values new:	3.000	1.800	0.900

New RPMs characteristically exhibit wide variation in retroreflectivity. The nominal values given above are merely statistical averages (arithmetic means) for Model 88 RPMs manufactured by Stimsonite that have been measured in the laboratory. It should be noted, in keeping with the rationale discussed in Section 2 regarding the differences between TTI and SDHPT laboratory measurement techniques, that the above values should be multiplied by 3.1416 (π) in order to express the equivalent SI as measured in the D-9 SDHPT Laboratory.

For convenience in preparation, since the retroreflective qualities of the various types of RPM's are the same from a perceptual standpoint, the test specimens were all Stimsonite Model 88.

Test Car

A 1979 Pontiac Grand Am 4-door was used for the test car. Test participants did not drive this car, but observed RPM's from the front seat passenger position. The car is equipped with state-of-the-art quartz iodide headlamps and a tinted windshield, consistent with the prevalence of air conditioning and such windshields in Texas. The car has a calibrated fifth wheel which directly reads in feet. The headlamps were aligned by target to nominal Texas standards for aiming (Periodic Motor Vehicle Inspection Manual, Current Issue). High beams were used throughout testing to illuminate the RPMs. The headlamps were measured from the specimen site to deliver an average of 0.041 ft-candle at 800 feet. This means that they had an equivalent intensity of 26,240 candela. Illuminance from the headlamps was measured before and after each experimental run.

Other Test Equipment

Simulation of an urban visual environment was accomplished by installing two types of luminaires in the test area. Luminaires on masts were used to simulate street lamps. A number of different colored lamps on stands were directed toward the observer to simulate the visual clutter often encountered in urban areas resulting from traffic signals, commercial signs and other traffic.

The simulated urban light environment produced an adapting illumination at the observer's eye of 0.68 ft-candles,

Figure 4-1 is a photograph of the urban setup taken at night. The test specimen is faintly visible (arrow).

Test specimens were placed in a special flat black holder for presentation to the observer in the test car. The holder ensured that the observation and entrance angles remained constant for all specimens.

Research Participants

Ten research participants were used. The 5 female and 5 male subjects ranged from 41 to 67 years old. Their salient characteristics are shown in Table 4-2. Middle-aged to older drivers were used because loss of visual acuity under night conditions as well as loss of light sensitivity related to pupillary limitations and opacity in the visual train are age-related. Thus, any threshold data derived from this sample could be expected to be conservative (that is, younger drivers could be expected to detect RPMs that were less retroreflective than those found to be just visible with this sample).

Research participants were licensed drivers, vision corrected. Their distance visual acuity was evaluated with a standard Ortho-

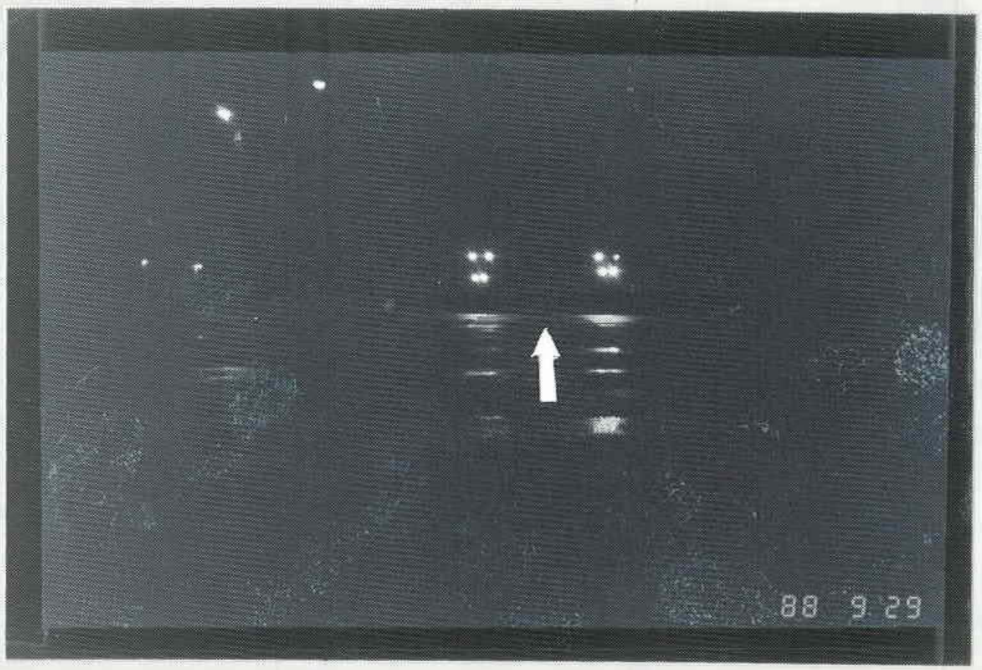

Figure 4-1. Urban environment visual scene.
(Arrow indicates faintly visible target RPM)

Table 4-2. Threshold study research participants.

Id No.	Gender	Age	Acuity
3	M	43	20/22
6	M	46	20/18
10	M	53	20/40
p1	M	59 *	
2	M	67	20/25
7	M	66	20/40
5	F	49	20/20
4	F	41	20/22
9	F	51	20/29
p2	F	53 *	
1	F	66	20/33
8	F	60	20/22

* Pilot study only

rater. Drivers not associated with TTI were paid $20.00 for their expenses associated with their participation on the project.

Test Design and Procedures

The test comprised a classic Method of Limits psychophysical approach. In this approach observers are presented test objects ranging from clearly below to clearly above their detection ability (threshold). The observer declares that he or she either sees or does not see the test object. The stimuli are presented in a random order to preclude anticipation. The observer does not know whether the next presentation will be faint, bright, or not visible at all. The results of such a test are then depicted as a probability curve for detecting the object. A number of presentations of the same object are made to assure reliability of the test results.

After executing an Informed Consent agreement, participants were given a standard visual acuity test using the Orthorater. None exhibited corrected acuity poorer than 20/40. The participant then was driven to the test site by an experimenter. The participant rode in the righthand front passenger seat of the test car. Half of the participants were tested under "rural" (dark) conditions first, half under "urban" (lighting in field of view) conditions first.

<u>"Rural" (Dark) Conditions</u>

The vehicle was positioned 800 feet from the test specimen location. On arrival at the site, the observer sat for at least five minutes before testing commenced to assure reasonable dark adaptation. The test site was on the East Apron of the Riverside Campus runway complex. The participant looked southward into a very dark background of trees and empty range land. Only one source of light at a great distance was visible, a yard lamp on a ranch far to the south of the Riverside Campus. This source of light was blocked during these tests by a strategically placed black-draped sign board. The experimenter in the test car communicated by radio with another experimenter at the specimen site who placed test specimens on signal. The trials commenced when twilight conditions gave way to night, with estimated ambient luminance in the mesopic range of 0.001 ft-lambert.

The research participant was read instructions which are provided as Figure 4-2. Following these instructions, the specimens were presented in rapid order according to a prearranged random ordering scheme. Each specimen was presented seven times. For each specimen presentation, the participant was asked to tell whether he or she could see the RPM, and if they could see it, what the color was. These responses were noted by the experimenter without comment, and the next presentation was then called for. This continued until all 126 presentations had been made.

Once the participant and experimenter had arrived at the test site and were in position, they sat for a period of 5-10 minutes to become dark adapted. The experimenter wore a 2-way radio head set to communicate with the assistant who positioned the test reflectors. The reflectors were labelled with arbitrary numbers to avoid encouraging the participant to associate the magnitude of the label with the brightness of the reflector. At this time the procedure was again explained to the participant:

> **You will be shown a series of reflectors of different colors and different brightnesses. They will always be in the same location. Some will be bright and some will not be; some may not even be there.**

A sample new reflector was placed in position to guide the participant's focus. It was made sure that the participant could see the reflector (If he could not see the new one, there was no point in continuing with the experiment). The explanation continued:

> **After the assistant positions the appropriate reflector and informs me that it is in place, I will tell you that it is in place and ask you to tell me whether or not you can see it and, if you can, what color you think it may be. Take all the time you need. If you are not sure if you can see it or ascertain its color, make the best possible guess that you can.**

New red, crystal, and amber reflectors (1 each) were set out such that the participant could see the selection of colors. After 1 minute, they were removed and the experiment began.

The experimenter held a flashlight with a red guard and kept it hidden so as not to alter the participant's dark adaptation. It was turned on only for data recording.

Figure 4-2. Testing procedure and instructions.

Urban (Light) Conditions

The procedures were the same as for "rural" conditions, with the following exceptions:

1. Distance from vehicle to test specimen was 400 ft.

2. The urban lighting simulation treatment was turned on, producing a higher level of light adaptation for the participant, in the neighborhood of 0.01 ft-lambert. The measured adapting illuminance at the observer's eye was 0.68 ft-candle. In these tests, the dome lamp of the vehicle was illuminated as part of the adapting illuminance. It should be pointed out that this setup was merely one of many different lighting situations that a driver might be confronted with in actual driving.

Verification of the Equivalence of Degraded and Reduced-Area RPMs

In this small investigation, three observers were used. The test vehicle was positioned approximately 400 ft from two specimens used on each trial. One specimen was made by degrading the amber reflective surface to an SI of 0.54. The other specimen was an undegraded identical RPM to the first, but with part of the surface covered with black electrician's tape to produce an SI equal to the first degraded specimen. The specimens were placed 3 feet apart on a line normal to the line of sight of the observer. The position of the taped and of the degraded reflector was varied randomly from trial to trial. The observers were asked to tell which of the two RPMs was the brighter. The car then moved slowly back until one or both disappeared. The car was then moved toward the specimens until the observer could identify which one appeared first. The car was then moved further toward the specimens until both were visible again. The sight distance was noted for each of these events. These trials were conducted under "rural" lighting conditions.

Results

"Rural" and "Urban" Lighting RPM Thresholds

Table 4-3 summarizes the results of the threshold study. Under Rural conditions, an older driver could be expected to detect an amber RPM in his headlamps (assuming that they were like those used in this study) roughly half the time at 800 ft if its SI were between 0.065 and 0.123, and would have no problems detecting it if it were brighter than 0.123 SI. Under much brighter seeing conditions, with other light sources in the field of view, a driver would not be able to pick such an RPM up until he or she approached to half that distance. Any amber RPM with an SI over 0.134 could be reliably detected at these distances. White, or crystal, RPMs can be reliably seen (approaching 100 per cent detection probability) at an SI value of about 0.19, whereas red RPMs can be readily seen at these distances with an SI of 0.16.

Table 4-3. Summary of results: Percent of RPMs detected as a function of color, specific intensity, and viewing condition.

RPM Color	SI	Rural (% Detected)	Urban (% Detected)
Red	.002	0.0	1.4
	.030	27.1	51.4
	.051	77.0	85.7
	.068	98.6	97.1
	.090	94.3	94.3
	.161	98.6	100.0
Amber	.005	1.4	0.0
	.013	1.4	1.4
	.015	4.3	5.7
	.065	32.9	48.6
	.123	98.6	98.6
	.134	94.3	92.9
Crystal	.007	1.5	1.4
	.051	3.8	51.4
	.068	1.4	85.7
	.080	1.1	97.1
	.120	11.4	94.1
	.188	95.2	100.0

If we take the conservative position that an RPM should be visible to the motoring public with 100% probability of detection, the thresholds derived from this study are (for 800-foot sight distance):

RPM Color	SI
Red	0.16
Amber	0.13
Crystal	0.19

The amount of light needed for equivalent visibility for nighttime seeing roughly doubles for each 13 years of age increment. Since the mean age of this sample was 54.5 years, doubling these SI's would accommodate drivers up to age 67, and doubling them again would make these RPMs visible to drivers up to 80 years of age. For 80-year-olds, these SI's would become:

RPM Color	SI
Red	0.64
Amber	0.52
Crystal	0.76

In order to generalize these results for a wide range of sight distances and levels of illumination by headlamps, let us convert these values for the sample and for the two extrapolations to 67 and 80 years of age from SI to illumination at the eyes from the equivalent point source represented by an RPM.

(1) $$SI = \frac{\text{Apparent Candlepower of RPM}}{\text{Illuminance from headlamps}}$$

or

$$SI = I_{rpm} / E$$

(2) $$I_{rpm} = SI \times E$$

Lambert's Law provides the illuminance at the eye produced by the RPM shining in the headlamps

(3) $$E_{rpm} = I_{rpm} / d^2$$

Using Lambert's Law for illuminance of headlamps

(4) $$E = I_{hl} / d^2$$

Substituting (2) and (4) into (3),

(5) Therefore $$E_{rpm} = (SI \times I_{hl}) / d^4$$

Where: I_{rpm} = Candlepower of RPM (Candela)
E = Illuminance from headlamps (ft-candles)
E_{rpm} = Illuminance from RPM to eyes (ft-candles)
d = distance from rpm to eyes (ft)
I_{hl} = Candlepower of Headlamps (Candela)

Using Equation 5 to convert the threshold data above, the following results are obtained (values in ft-candles x 10^{-8}):

	Age		
Color	54.5 yrs	67 yrs	80 yrs
Red	1.025	2.050	4.100
Amber	0.832	1.664	3.328
Crystal	1.217	2.434	4.869

These results say that, for example, a person represented by our test sample would be able to detect on a dark road any source of light that delivers 0.0000001025 ft-candle of light to his eyes. When an RPM gets close enough that the reflection from it reaches that value, he or she will be certain to see it. In contrast, an 80-year-old driver would need to have 0.0000004869 ft-candle in order to have the same assurance of seeing the reflector. It would have to be four times brighter. An engineer need only substitute into Equation 5 the required sight distance needed at a particular location on a highway, a nominal value of headlamp intensity (20,000 might be a good number, based on SAE J579) and the age/color equivalent intensity of an RPM tabled above to determine the SI of an RPM that would yield the 100 per cent detection threshold. A set of such calculations for various sight distances is provided in the Table 4-4 for a nominal headlamp intensity of 20,000 candela. These values would not hold for the "urban" condition in which the driver's eyes are much more light adapted and not as sensitive. The single condition simulated in this study cannot be generalized to all urban circumstances. Under the urban condition set up in this study, the 80-year-old amber threshold illuminance by an RPM becomes 0.000000349 ft-candles (using Eq.4), which represents an increase in brightness of almost an order of magnitude (10 times)!

These thresholds are "achromatic," that is to say, the drivers were reporting detection of an object as a point of light. They often were unsure as to the color of the RPM that they were seeing, particularly amber vs white or crystal. Red was almost always correctly identified.

Table 4-4. Predicted specific intensity thresholds for 80-year-old drivers, RPMs illuminated by 20,000 candela headlamps.

Distance(ft)	Red RPM SI	Amber RPM SI	Crystal RPM SI
50	.0000	.0000	.0000
100	.0002	.0002	.0002
150	.0010	.0009	.0012
200	.0033	.0027	.0039
250	.0080	.0065	.0095
300	.0166	.0135	.0197
350	.0308	.0250	.0365
400	.0525	.0426	.0623
450	.0841	.0682	.0998
500	.1281	.1040	.1522
550	.1876	.1523	.2228
600	.2657	.2156	.3155
650	.3659	.2970	.4346
700	.4922	.3995	.5845
750	.6486	.5265	.7703
800	.8397	.6816	.9972

These results are comparable to those found by other researchers dating back to 1946 and before. They represent the lowest practicable bounds for degradation of RPMs installed on the highways. The seeing conditions in the "rural" situation were ideal for detecting these objects: no distractions, not driving, good visibility, very dark environment, and knowledge that an object was present. Hence it can be said with some confidence that RPMs that have degraded to such an extent that they can no longer deliver the threshold amount of light to the eye at the needed sight distance with the dimmest legal headlamps definitely need to be replaced. This study sets the lower limit of usability.

Discrimination Between Degraded and Masked Test Specimens

No significant differences were noted in sight distances between equivalent SI RPMs which were abraded on the reflective surface, vs those taped to occlude part of the reflective surface. The two observers were unable to discriminate between the two types of devices. This demonstration confirms the assertion that at the operating distances used to illuminate and view RPMs, they are point sources of light.

Threshold Study 2: An Analysis of Threshold Specific Intensities to Account for Rain Diffusion

The results of Study 1 document the threshold specific intensities for observers under two different lighting conditions. In the discussion of those results, a rationale was presented for predicting the lowest illuminance from a point source of light, such as an RPM lit by headlamps, that a driver might be able to discern with high certainty. These values, repeated below, are valid for reasonably dark, clear seeing conditions (all values in ft-candles x 10^{-8}):

	Age		
Color	54.5 yrs	67 yrs	80 yrs
Red	1.025	2.050	4.100
Amber	0.832	1.664	3.328
Crystal	1.217	2.434	4.869

As would be expected, the elderly driver (80 years of age) needs considerably more illumination from an RPM to see it, thus providing a "worst case" for design purposes. Study 2 provides an analysis and discussion of the influence of rain on the predicted RPM intensity requirements for these drivers.

In order for a driver to see a light source, the specified amount of illumination to the eye must be provided regardless of what the light has to traverse before impinging on the eye. In the case of an RPM on a rainy night, the attenuation introduced by the environment can be a very significant factor.

To assess the extent of light attenuation due to rain, the values in Table 4-4 (from Study 1) can be corrected to account for various rainfall rates. It will be recalled that Table 4-4 provides predicted SI (in the usual candela per incident foot-candles) for all three colors of roadway RPMs as a function of sight distance, ranging from 50 feet to 800 feet. This table assumes clear seeing conditions: dry, dark road, no opposing traffic, no rain or mist in the air. The headlamps illuminating the RPM are assumed to be at nominal high-beam level of 20,000 candela, again a conservative assumption.

If we now assume that the driver is looking at the RPM through a downpour, the light from the headlamps is scattered and absorbed as it travels to the RPM. The light returning from that RPM is likewise scattered and attenuated by the rain. Ivey, Lehtipuu, and Button (1975) studied visibility through rainfall. They found that rainfalls exceeding 1 inch per hour, even in areas of Texas where heavy rainfall is common, were rarely encountered (less than 5 hours per year). Ivey et al recommended a "design rainfall" of 1 inch per hour for further analysis. In order to bracket the situation, we shall use this level of rainfall, plus values of 0.5

inch per hour and 2 inches per hour. In a relatively qualitative estimate of daylight visibility, Ivey et al associated a 1-inch-per-hour rainfall with a 30 percent loss in visibility in a car travelling 50 MPH. A 2-inch-per-hour rainfall intensity reduces visibility to less than 50 percent of clear conditions.

Atlas (1953) developed an analysis of optical extinction by rainfall in which he derived a coefficient of atmospheric extinction:

(6) $$s = 5.85R^{0.63} \times 10^{-4}$$

Where R = rainfall, in/hr

The extent to which the medium through which light is travelling absorbs or scatters that light is expressed by "s". There is a straightforward relationship between s and "t" which is transmissivity, a term encountered in meteorology, aviation, and many other places. The conversion (Middleton, 1952) is as follows:

(7) $$t = e^{-s}$$

Where e = natural log base

Allard's Law (IES, 1966) relates illuminance provided by a source shining through a medium for which the transmissivity is known by the simple relationship:

(8) $$E = I\ t^{d}/d^{2}$$

Where E = Illuminance
I = Intensity of the source
d = distance

Using these relationships, a table of predicted threshold SI for red, amber and crystal RPMs was generated and is given as Table 4-5. As a function of distance in feet, equations 7 and 8 are used to compute transmissivity over the distance (t^d) under the three conditions of rainfall, 0.5, 1, and 2 inches per hour. "Clear" visibility SI is reproduced from Table 4-4. For example, at 50 feet, the transmissivity factor is 0.9712 for 1 inch per hour rain, a loss of 3 percent. For the same condition, equation 8 is used to compute an illuminance provided by the 20,000 candela headlamps assumed in this table. For this same example, the illuminance would be 7.7693 ft-candles impinging on an RPM in the road. Equation 8 is also used to compute the intensity required of an RPM to permit it to be seen by an 80-year-old observer. For this calculation, the illuminance values provided by Study 1 are used. For a red RPM, the illuminance that must be delivered to the eyes is 0.000000041 ft-candle. In order for the RPM to be seen at 50 feet through a rainfall of 1 inch per hour, Equation 8 is solved for I, intensity. The intensity need be only 0.0001. This means that even a "dead" RPM could be seen easily. The ratio of required I (Intensity) for the RPM to the incident illuminance of the headlamps yields the estimate of the SI required for visibility, in this case, zero.

The picture radically changes with distance, however. Take the case of an amber RPM. At 400 feet, under clear seeing conditions, the device needs to have an SI of 0.0426 or 0.04 to be seen by an 80-year-old. If the rainfall through which our elderly driver is peering is 1 inch per hour, the SI needed jumps up to 0.068. At 800 feet, the difference is from 0.68 to 1.7. This means that only a brand-new RPM could be seen through this rain by an older driver! SI's greater than 2 are rarely attainable with amber RPMs; therefore even a brand new amber RPM could not be discerned by a typical 80-year- old driver in a 2-inch-per-hour rainstorm at 750 or more feet.

Table 4-5 suggests that for a heavy downpour of 2 inches/hour, a red RPM could be glimpsed at 250 feet if it were degraded to 0.01 SI (a level commonly found after an RPM has been in place for a year or more). An amber RPM degraded to the same level could only be seen 150 feet distant. A crystal or white RPM could be seen about as far away as a red RPM.

The values given in Table 4-5 represent an estimate of RPM visibility under dark, rainy conditions. These represent the very best that could be expected, since several very significant factors are not taken into account,including:

1. Windshield smearing and water scatter from motion of the car,
2. Moisture on the face of the RPM, and
3. Reflections from the wet roadway.

These estimates are refined on the basis of data collected in Study 3.

Table 4-5. Predicted specific intensity thresholds for 80-year-old drivers under clear and rainy conditions, RPMs illuminated by 20,000 candela headlamps.

RPM COLOR: RED

Feet	Threshold SI	Transmissivity of Rainfall			Illuminance of Headlamps			Luminance of RPM Req'd to See			Threshold RPM SI in Rain		
	(Clear)	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*
50	.0000	.9813	.9712	.9557	7.8502	7.7693	7.6459	.0001	.0001	.0001	.0000	.0000	.0000
100	.0002	.9629	.9432	.9134	1.9258	1.8863	1.8269	.0004	.0004	.0004	.0002	.0002	.0002
150	.0010	.9449	.9160	.8730	.8399	.8142	.7760	.0010	.0010	.0011	.0012	.0012	.0014
200	.0033	.9272	.8896	.8344	.4636	.4448	.4172	.0018	.0018	.0020	.0038	.0041	.0047
250	.0080	.9098	.8639	.7975	.2911	.2764	.2552	.0028	.0030	.0032	.0097	.0107	.0126
300	.0166	.8928	.8390	.7622	.1984	.1864	.1694	.0041	.0044	.0048	.0208	.0236	.0286
350	.0308	.8761	.8148	.7284	.1430	.1330	.1189	.0057	.0062	.0069	.0401	.0463	.0580
400	.0525	.8597	.7913	.6962	.1075	.0989	.0870	.0076	.0083	.0094	.0710	.0838	.1083
450	.0841	.8436	.7685	.6654	.0833	.0759	.0657	.0098	.0108	.0125	.1181	.1423	.1899
500	.1281	.8278	.7463	.6359	.0662	.0597	.0509	.0124	.0137	.0161	.1870	.2300	.3168
550	.1876	.8123	.7248	.6078	.0537	.0479	.0402	.0153	.0171	.0204	.2843	.3571	.5078
600	.2657	.7970	.7039	.5809	.0443	.0391	.0323	.0185	.0210	.0254	.4182	.5362	.7873
650	.3659	.7821	.6836	.5552	.0370	.0324	.0263	.0221	.0253	.0312	.5982	.7830	1.1872
700	.4922	.7675	.6639	.5306	.0313	.0271	.0217	.0262	.0303	.0379	.8356	1.1167	1.7482
750	.6486	.7531	.6448	.5071	.0268	.0229	.0180	.0306	.0358	.0455	1.1436	1.5603	2.5221
800	.8397	.7390	.6262	.4847	.0231	.0196	.0151	.0355	.0419	.0541	1.5375	2.1416	3.5743

RPM COLOR: AMBER

Feet	Threshold SI	Transmissivity of Rainfall			Illuminance of Headlamps			Luminance of RPM Req'd to See			Threshold RPM SI in Rain		
	(Clear)	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*
50	.0000	.9813	.9712	.9557	7.8502	7.7693	7.6459	.0001	.0001	.0001	.0000	.0000	.0000
100	.0002	.9629	.9432	.9134	1.9258	1.8863	1.8269	.0003	.0004	.0004	.0002	.0002	.0002
150	.0008	.9449	.9160	.8730	.8399	.8142	.7760	.0008	.0008	.0009	.0009	.0010	.0011
200	.0027	.9272	.8896	.8344	.4636	.4448	.4172	.0014	.0015	.0016	.0031	.0034	.0038
250	.0065	.9098	.8639	.7975	.2911	.2764	.2552	.0023	.0024	.0026	.0079	.0087	.0102
300	.0135	.8928	.8390	.7622	.1984	.1864	.1694	.0034	.0036	.0039	.0169	.0191	.0232

* Rainfall in inches per hour

Table 4-5 (Cont'd)

Feet	Threshold SI (Clear)	Transmissivity of Rainfall			Illuminance of Headlamps			Luminance of RPM Req'd to See			Threshold RPM SI in Rain		
		0.5*	1.0*	2.0*	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*
350	.0250	.8761	.8148	.7284	.1430	.1330	.1189	.0047	.0050	.0056	.0325	.0376	.0471
400	.0426	.8597	.7913	.6962	.1075	.0989	.0870	.0062	.0067	.0076	.0576	.0680	.0879
450	.0682	.8436	.7685	.6654	.0833	.0759	.0657	.0080	.0088	.0101	.0959	.1155	.1541
500	.1040	.8278	.7463	.6359	.0662	.0597	.0509	.0101	.0111	.0131	.1518	.1867	.2572
550	.1523	.8123	.7248	.6078	.0537	.0479	.0402	.0124	.0139	.0166	.2308	.2898	.4122
600	.2157	.7970	.7039	.5809	.0443	.0391	.0323	.0150	.0170	.0206	.3395	.4352	.6391
650	.2970	.7821	.6836	.5552	.0370	.0324	.0263	.0180	.0206	.0253	.4856	.6356	.9637
700	.3995	.7675	.6639	.5306	.0313	.0271	.0217	.0212	.0246	.0307	.6783	.9064	1.4190
750	.5265	.7531	.6448	.5071	.0268	.0229	.0180	.0249	.0290	.0369	.9283	1.2665	2.0472
800	.6816	.7390	.6262	.4847	.0231	.0196	.0151	.0288	.0340	.0439	1.2480	1.7383	2.9013

RPM COLOR: CRYSTAL

Feet	Threshold SI (Clear)	Transmissivity of Rainfall			Illuminance of Headlamps			Luminance of RPM Req'd to See			Threshold RPM SI in Rain		
		0.5*	1.0*	2.0*	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*	0.5*	1.0*	2.0*
50	.0000	.9813	.9712	.9557	7.8502	7.7693	7.6459	.0001	.0001	.0001	.0000	.0000	.0000
100	.0002	.9629	.9432	.9134	1.9258	1.8863	1.8269	.0005	.0005	.0005	.0003	.0003	.0003
150	.0012	.9449	.9160	.8730	.8399	.8142	.7760	.0012	.0012	.0013	.0014	.0015	.0016
200	.0039	.9272	.8896	.8344	.4636	.4448	.4172	.0021	.0022	.0023	.0045	.0049	.0056
250	.0095	.9098	.8639	.7975	.2911	.2764	.2552	.0033	.0035	.0038	.0115	.0127	.0150
300	.0197	.8928	.8390	.7622	.1984	.1864	.1694	.0049	.0052	.0057	.0247	.0280	.0339
350	.0365	.8761	.8148	.7284	.1430	.1330	.1189	.0068	.0073	.0082	.0476	.0550	.0688
400	.0623	.8597	.7913	.6962	.1075	.0989	.0870	.0091	.0098	.0112	.0843	.0995	.1286
450	.0998	.8436	.7685	.6654	.0833	.0759	.0657	.0117	.0128	.0148	.1403	.1690	.2255
500	.1522	.8278	.7463	.6359	.0662	.0597	.0509	.0147	.0163	.0191	.2221	.2732	.3762
550	.2228	.8123	.7248	.6078	.0537	.0479	.0402	.0181	.0203	.0242	.3377	.4240	.6030
600	.3155	.7970	.7039	.5809	.0443	.0391	.0323	.0220	.0249	.0302	.4966	.6368	.9350
650	.4346	.7821	.6836	.5552	.0370	.0324	.0263	.0263	.0301	.0371	.7104	.9299	1.4099
700	.5845	.7675	.6639	.5306	.0313	.0271	.0217	.0311	.0359	.0450	.9924	1.3262	2.0761
750	.7703	.7531	.6448	.5071	.0268	.0229	.0180	.0364	.0425	.0540	1.3581	1.8529	2.9951
800	.9972	.7390	.6262	.4847	.0231	.0196	.0151	.0422	.0498	.0643	1.8259	2.5432	4.2447

Threshold Study 3: Thresholds for Detection of Retroreflective Raised Pavement Markers under Simulated Wet Weather Conditions

Introduction

This experiment was designed to extend the findings of the first study in detection thresholds for retroreflective raised pavement markers (RPM) under good seeing conditions to the situation in which the pavement is flooded and opposing traffic headlamps are both causing specular reflections from the flooded pavement and reducing the dark adaptation of the observer. Under these conditions of seeing, the minimum specific intensities that would be expected to be at near 100 percent threshold will be far higher than found in the first study. Data derived from this experiment was then corrected using factors developed and discussed in Study 2: An Analysis of Threshold Intensities to Account for Rain Diffusion.

Method

Equipment

1. 1979 Pontiac Grand Am used in Study 1. This car is equipped with quartz iodide headlamps that produce a nominal 26,240 candela (high beam), and 33,600 candela (low beam) at 200 feet directly in front of the vehicle. (Figure 4-3)

2. Water distribution system. The water distribution system used for TTI truck splash and spray investigations was used to provide water on the test pad sufficient to produce a flooded, specular condition between the observer and the test apparatus (approximately 0.05 inch).

3. Rotating shutter apparatus for exposing a test RPM to the observer. This device consists of a 5-inch radius disk with a slot cut in its outer periphery. The disk is mounted vertically on a 1 rpm motor driven shaft such that an RPM behind the disk is gradually revealed and then concealed. The effect of this device, when illuminated by headlamps and viewed at a distance, is to make the point source of light produced by an RPM seem to grow brighter and brighter until it is fully exposed, then diminish in brightness until it can no longer be seen. By pressing a switch wired to break a latch circuit, an observer can stop the shutter at any point. The shutter disk is equipped with a vernier scale to permit its position with respect to the test RPM to be measured. The scale measurement is calibrated to provide conversion of the angular data to specific intensity of the exposed RPMs. This apparatus is depicted in Figures 4-4 and 4-5.

Figure 4-3. Test observer vehicle.

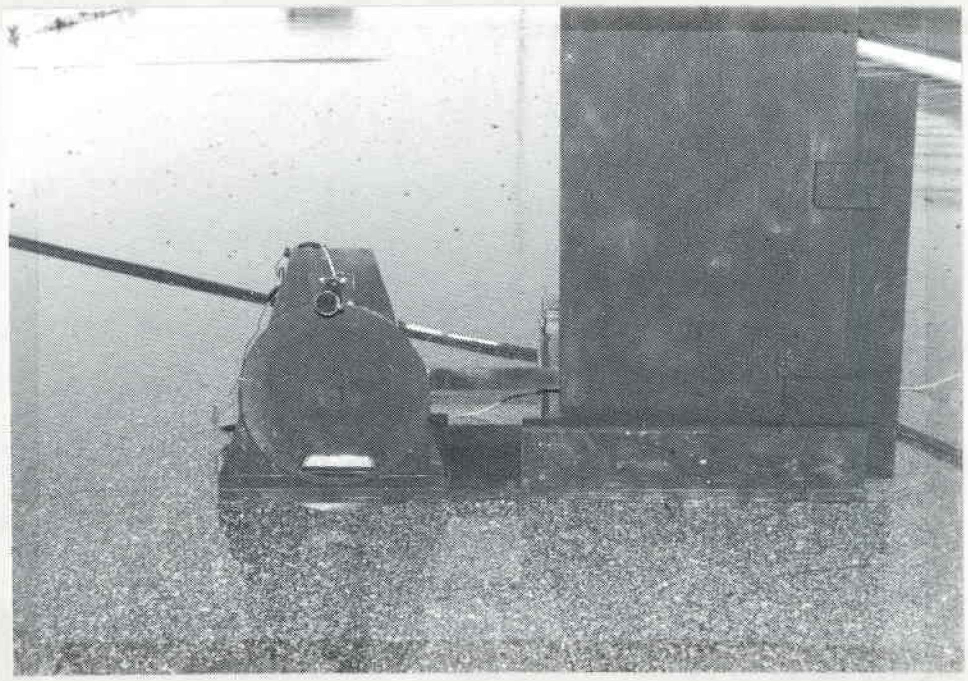

Figure 4-4. Shutter apparatus for presenting RPMs

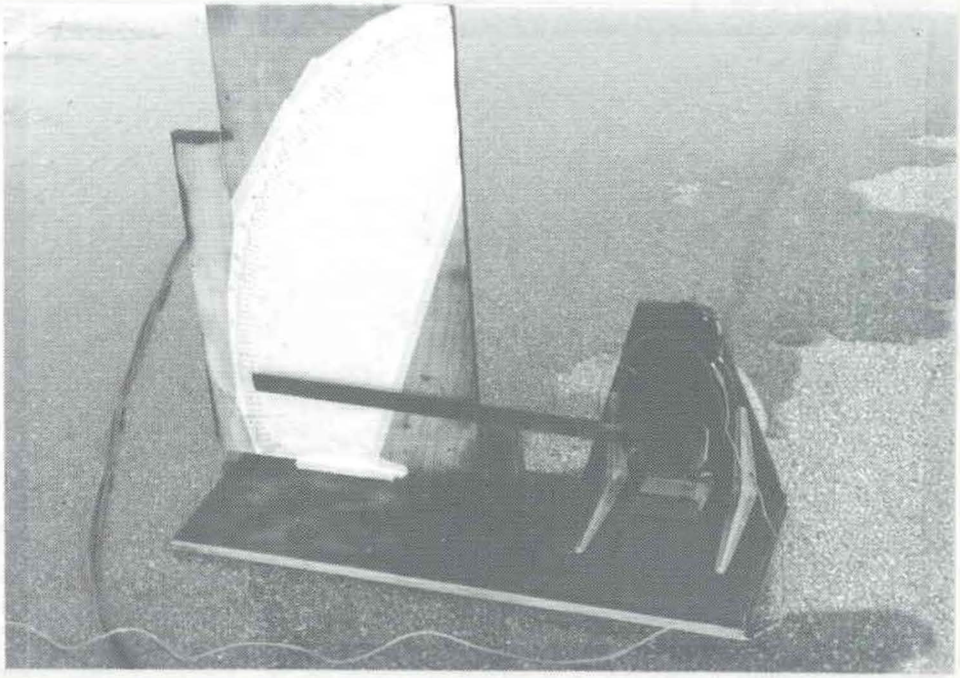

Figure 4-5. Rear view of shutter apparatus

Figure 4-6. "Opposing traffic" vehicle.

4. RPM specimens prepared for this study were Stimsonite Type 88, in red, amber and white. They were reduced by area adjustmentto 50 per cent of their nominal full SI value.

5. An opposing vehicle which was stationed just off the test pad as though it were in an opposing traffic lane on a two lane highway. This vehicle had its low beam headlamps on. The vehicle, a 1981 Cadillac Coupe DeVille depicted in Figure 4-6, was positioned 200 feet north of the test RPM. The car's headlamps delivered 0.156 ft-candles of illuminance to the observer, 400 feet away. The headlamp's equivalent candlepower was, accordingly, 25,960 candela.

Research Participants

Fourteen research participants were recruited to work in this study. Age, gender and corrected acuity data for these individuals are summarized in Table 4-6. Of this group, participants 11 and 12 were eliminated, because they were unable to discern any objects at any brightness in the glare from the headlamps of the opposing vehicle. They were very sensitive to glare at night, and neither drove at night.

Procedure

The method was the classic psychophysical Method of Adjustment. Each observer was driven to the test site and then stationed behind the wheel of the test vehicle already positioned on the test surface. Low beam headlamps were used. The test location for this vehicle was 200 feet south of the test RPM in its

Table 4-6. Study 3 research participants.

Participant No.	Gender	Age	Visual Acuity
1	F	52	20/29
2	M	53	20/40
3	M	54	20/20
4	M	67	20/40
5	M	68	20/29
6	F	66	20/29
7	F	73	20/20
8	M	60	20/20
9	M	69	20/18
10	M	69	20/25
11	F	77	20/40, 20/50
12	F	71	20/40
13	F	60	20/20
14	F	57	20/20

rotating shutter device. The RPM in its shutter was positioned on the flooded road surface, in the water. Figure 4-7 shows the scene from the observer's viewpoint in daylight, and Figure 4-8 shows it at night. The line of RPMs on the left are for a durability study and were not involved in this experiment.

At the beginning of a test sequence, the observer was told to observe the RPM and watch for its disappearance. The experimenter at the site then started the shutter rotating. As the shutter covered the RPM, the observer attended the visual scene, and when he or she lost sight of the RPM, the observer depressed a stop button. This broke the circuit to the rotating shutter motor. The test site experimenter then read the shutter position scale. The position scale corresponded to the amount of RPM reflective area exposed, which, in turn, was indicative of the SI of the exposed RPM. The shutter was activated again and the observer was now instructed to watch for the reappearance of the RPM. The observer was instructed to press the button again when the RPM just appeared. The shutter position was then again read. The mean of these two readings was taken as the threshold value. The procedure was followed for all three colors, with twelve replications per color.

Results

Table 4-7 presents a summary of test results for the 12 participants that were able to see through the glare. Values for the raised pavement markers are in terms of specific intensity (SI), candela per incident ft-candles. Mean (average) SI for red markers was 0.104, 0.240 for amber, and 0.229 for clear or crystal RPMs. By using the sample standard deviation or RMS error also reported in Table 4-7, and data reported from Study 1 in this series, some conclusions can be drawn concerning minimum values of SI for various sight distances and weather conditions.

<u>Estimate of Minimum Acceptable Illuminance at Eye from RPM</u>

By using the standard deviation computed from the data on the 12 participants, a 95 percent confidence interval can be estimated. If the sample taken in this study approximates the parameters of the population of older middle-age drivers from which it was drawn, 95 percent of the thresholds measured under the seeing conditions of this study should fall within plus or minus 2 standard deviations from the mean. If only about half of the population could reliably see an amber RPM under these conditions with an SI of 0.24, then 95 percent should be able to see an RPM with an SI = 0.24 + (2 x 0.187) = 0.614.

Figure 4-7. Test setup from observer vehicle (daylight).

Figure 4-8. Test setup from observer vehicle (night).

Table 4-7. Threshold specific intensities, Threshold Study 3.

Test Conditions: Observer vehicle 200 ft from RPM.
Low beam headlamps.
Low beam opposing vehicle, 200 ft beyond RPM.
Wet pavement.

Subject	RPM Color Amber	Red	Crystal
1	.045	.045	.082
2	.239	.052	.244
3	.158	.095	.185
4	.205	.185	.139
5	.757	-	.475
6	-	-	-
7	.248	.164	.377
8	.321	.147	.313
9	.168	.088	.196
10	.164	.085	.175
13	.110	.104	.115
14	.222	.071	.213
Mean	.240	.104	.229
Std. Dev.	.187	.047	.118

Calculations like this lead to the following results:

Amber RPM	SI = 0.614	Candela = 0.516
Red RPM	SI = 0.198	Candela = 0.166
Crystal RPM	SI = 0.465	Candela = 0.391

The equivalent candlepower of the RPM as reflected in this table is computed by multiplying the SI by the illuminance from the vehicle's headlamps, which was measured to be 0.84 ft-candle. These values lead directly to an estimate of how much light must fall on the observer's eyes in order for 95 per cent of a sample of people ranging in age in from their late 50's to early 60's to say that they see an RPM. Invoking Lambert's Inverse Square Law, the equivalent candlepower of each RPM above is divided by the square of the distance between the RPM and the observer (200 ft x 200 ft) to yield the following values:

Amber RPM	Illuminance at eyes = 0.0000129 ft-candle
Red RPM	Illuminance at eyes = 0.00000415 ft-candle
Crystal RPM	Illuminance at eyes = 0.00000977 ft-candle

These three numbers represent the best conservative estimate of the amount of light that must fall on an observer's eyes from an RPM when he or she is looking at oncoming traffic on a dark and wet road and trying to see the marker. From a target detection standpoint, this is "worst case" for design purposes.

Comparison with Theoretical Estimate for Elderly Driver

In Study 1 of this series, "Threshold Specific Intensities of Retroreflective Raised Pavement Markers," an extrapolation was made to the vision of an 80-year-old person. Using the rule that the amount of light needed for threshold detection doubles every 13 years, a correction factor of 3.1 could be applied to the above data to derive an equivalent 80-year-old threshold from the 60-year-old threshold data. The multiplier applied to the mean thresholds would yield these results:

Amber RPM	Illuminance at eyes = 0.0000157 ft-candle
Red RPM	Illuminance at eyes = 0.00000677 ft-candle
Crystal RPM	Illuminance at eyes = 0.0000162 ft-candle

Illuminances of this level would permit at least half of those 80 years old to discern an RPM. They are not very much different than the 95 percent confidence level 60-year-old thresholds described in the last section. If those thresholds are multiplied by 3.1, then everyone 80 years or younger with normal or correctable vision should be able to see the RPMs, if the deleterious effects of glare were not a problem to elderly observers.

Observers much over 70 tend to have a great deal of problem with nighttime glare, as evidenced by two of the 14 participants in this study. Hence these theoretical thresholds are probably suspect, because in fact many 80-year-olds would be unable to make out the RPM in the veiling glare. Thus further analysis of the data in this experiment will use the 95 percent 60-year-old average age observer thresholds, with a caveat that some very elderly drivers (perhaps half of those averaging 80 years of age) would probably be able to discern RPMs delivering that amount of light, but many would have problems.

Prediction of RPM Visibility as a Function of Distance and Rainfall

The rationale for computing threshold RPM specific intensity as a function of seeing distance and rainfall is explained in Study 2. Generation of the tables and graphs for this analysis assumes a nominal value of 20,000 candela for the equivalent candlepower of the observer's vehicle headlamps. This value is picked from the range of 18,000 to 30,000 candela for low beam lamps reported in Perel, et al (1983).

The "Clear" column in Table 4-8 provides the threshold SI for red, amber, and crystal RPMs on wet pavement, with opposing traffic but no rain as a function of sight distance in increments of 50 feet. In the case of amber RPM's, perhaps the most critical color of marker, sight distances of over 250 feet are not attainable, since a brand new marker does well to yield an SI of 2. Under conditions in which light is attenuated by rainfall, not much more than 200 feet can be attained with a new marker. The typical marker which has been in place for a year or so, and has an SI of 0.1 or less would not be usable at distances much beyond 100 ft. Similar results are shown in Table 4-8 for red and crystal markers.

For comparison, two other cases previously investigated (and reported in Study 1) are analyzed in the same fashion and shown in Tables 4-9 and 4-10, for the perfect-seeing dark road condition, and for a nominal "urban" condition which does not involve opposing traffic. In Table 4-9, it can be seen that a somewhat degraded amber RPM with an SI of 0.36 can be seen at 800 feet and can be picked up at 600 feet even in a driving rainstorm of 2 inches per hour. An RPM with the "typical" SI of 0.1 could be seen at 600 feet and at a little less than 500 feet in the rainstorm. In the nominal "urban" circumstance, such a marker could be seen at 300 feet in the clear and somewhat over 250 feet in the 2-inch-per-hour downpour.

Figures 4-9, 4-10 and 4-11 are plots of threshold SI for amber RPMs for the three scenarios that were discussed, based on the tabled data. Figure 4-9 presents the findings for the opposing traffic, wet pavement condition, Figure 4-10 shows thresholds for the clear but wet pavement seeing condition, and Figure 4-11 depicts the nominal "urban" situation.

Summary of Findings

The geometrics of a particular highway setting dictate how far away an RPM needs to be seen in order to provide proper guidance to the driver. Many jurisdictions use a "rule of three" to set guidelines for RPM visibility: at any given point on the highway, at least three RPMs must be above threshold to provide path information. Add to this a rule of thumb which is widely endorsed in traffic engineering circles: 2.5 seconds decision-response time. (ITE, 1976) If a driver is travelling at 55 MPH (80.7 feet/sec), he or she needs to see the farthest of three RPMs at a distance of 2.5 x 80.7 = 201.8 or 200 feet. In curved sections at reduced speeds, or under wet weather conditions in which average speeds would be lower, this decision sight distance decreases proportionately.

If the traffic engineer assumes a "worst case" situation with a wet, shiny pavement, glaring headlamps in the opposing lane, and rain falling (but assuming good visibility through the windshield - a perhaps dubious assumption) then reference to Table 4-8 gives the minimum level of SI at which replacement should be considered. For example, in areas subject to downpours of up to 2 inches per hour, assuming a 200 foot sight distance requirement and traffic at 55 MPH, amber RPMs should exhibit SIs no less than 1.5. Similarly, crystal and red RPMs can be expected to function at SIs of 1.1 and 0.5, respectively. For sites at which little rainfall occurs, the "Clear" column could be used, indicating SIs of 1 for amber, 0.8 for crystal, and 0.3 for red RPMs.

Suppose that opposing traffic glare is not a problem, but the other assumptions hold: 55 MPH, 2.5 second decision-sight distance, and "urban" lighting conditions similar to that in a strip business district. Then Table 4-10 would give some values for minimum SI. Under heavy rain (2 inches per hour) amber RPMs would be replaced when their SI fell below 0.03, crystal at an SI of 0.04, and red units under 0.03.

Table 4-9 yields equivalent figures for very dark situations which might occur in farm-to-market or other rural roads.

Thus these findings strikingly emphasize the importance of operational, geometric, and weather considerations in deciding when an RPM is no longer effective in its place.

Table 4-8. Predicted threshold SI as a function of distance and rainfall. Adapting condition for observer:

Opposing traffic
Wet pavement
Headlamp illuminance = 20,000 candela.

	Detection Distance (ft)	Clear	Rainfall Rate 0.5 In/Hr	1 In/hr	2 In/hr
RPM COLOR: AMBER					
	50	0.004	0.004	0.004	0.004
	100	0.06	0.07	0.07	0.08
	150	0.33	0.37	0.39	0.43
	200	1.03	1.20	1.30	1.48
	250	2.52	3.04	3.38	3.96
RPM COLOR: CRYSTAL					
	50	0.003	0.003	0.003	0.003
	100	0.05	0.05	0.06	0.06
	150	0.25	0.28	0.30	0.32
	200	0.78	0.91	0.99	1.12
	250	1.91	2.30	2.56	3.00
RPM COLOR: RED					
	50	0.001	0.001	0.001	0.001
	100	0.02	0.02	0.02	0.03
	150	0.11	0.12	0.13	0.14
	200	0.33	0.39	0.42	0.48
	250	0.81	0.98	1.09	1.28
	300	1.68	2.11	2.39	2.89

Table 4-9. Predicted threshold SI as a function of distance and rainfall. Adapting condition for observer:

Dark highway, no ambient lighting
Headlamp Illuminance: 20,000 candela

	Detection Distance (ft)	Clear	Rainfall Rate 0.5 In/Hr	1 In/hr	2 In/hr
RPM COLOR: AMBER					
	50	0.000	0.000	0.000	0.000
	100	0.000	0.000	0.000	0.000
	150	0.000	0.000	0.000	0.000
	200	0.001	0.002	0.002	0.002
	250	0.003	0.004	0.01	0.01
	300	0.01	0.01	0.01	0.01
	350	0.01	0.02	0.02	0.03
	400	0.02	0.03	0.04	0.05
	450	0.04	0.05	0.06	0.08
	500	0.05	0.08	0.10	0.13
	550	0.08	0.12	0.15	0.22
	600	0.11	0.18	0.23	0.33
	650	0.16	0.25	0.33	0.50
	700	0.21	0.35	0.47	0.74
	750	0.27	0.48	0.66	1.07
	800	0.36	0.65	0.91	1.51
RPM COLOR: CRYSTAL					
	50	0.000	0.000	0.000	0.000
	100	0.000	0.000	0.000	0.000
	150	0.001	0.002	0.001	0.001
	200	0.002	0.002	0.002	0.003
	250	0.005	0.005	0.006	0.007
	300	0.009	0.01	0.01	0.02
	350	0.02	0.02	0.03	0.03
	400	0.03	0.04	0.05	0.06
	450	0.05	0.07	0.08	0.11
	500	0.07	0.10	0.13	0.18
	550	0.10	0.16	0.20	0.28
	600	0.15	0.23	0.30	0.44
	650	0.20	0.33	0.44	0.66
	700	0.27	0.46	0.62	0.97
	750	0.36	0.64	0.87	1.40
RPM COLOR: RED					
	50	0.000	0.000	0.000	0.000
	100	0.000	0.000	0.000	0.000
	150	0.000	0.000	0.000	0.001
	200	0.001	0.001	0.001	0.002
	250	0.003	0.003	0.004	0.004
	300	0.006	0.007	0.008	0.01
	350	0.01	0.01	0.02	0.02
	400	0.02	0.02	0.03	0.04
	450	0.03	0.04	0.05	0.06
	500	0.04	0.06	0.08	0.11
	550	0.06	0.09	0.12	0.17
	600	0.09	0.14	0.18	0.26
	650	0.12	0.20	0.26	0.39
	700	0.16	0.28	0.37	0.58
	750	0.21	0.38	0.52	0.84
	800	0.28	0.51	0.71	1.18

Table 4-10. Predicted threshold SI as a function of distance and rainfall. Adapting condition for observer:

Urban Corridor, no opposing traffic
Headlamp Illuminance = 20,000 candela

	Detection Distance (ft)	Rainfall Rate Clear	0.5 In/Hr	1 In/hr	2 In/hr
RPM COLOR: AMBER					
	50	.00	.00	.00	.00
	100	.00	.00	.00	.00
	150	.01	.01	.01	.01
	200	.02	.03	.03	.03
	250	.05	.06	.07	.08
	300	.11	.14	.16	.19
	350	.20	.26	.31	.38
	400	.35	.47	.55	.71
	450	.55	.78	.94	1.25
	500	.85	1.23	1.52	2.09
	550	1.24	1.88	2.36	
	600	1.75			
	650	2.42			
RPM COLOR: CRYSTAL					
	50	.00	.00	.00	.00
	100	.00	.00	.00	.00
	150	.01	.01	.01	.01
	200	.03	.03	.03	.04
	250	.07	.08	.09	.10
	300	.14	.17	.19	.23
	350	.25	.33	.38	.47
	400	.43	.58	.68	.88
	450	.69	.96	1.16	1.55
	500	1.04	1.52	1.87	2.58
	550	1.53	2.32	2.91	4.14
	600	2.17	3.41	4.37	
	650	2.98	4.88		
	700	4.01			
RPM COLOR: RED					
	50	.00	.00	.00	.00
	100	.00	.00	.00	.00
	150	.01	.01	.01	.01
	200	.02	.02	.02	.03
	250	.05	.06	.06	.07
	300	.09	.12	.13	.16
	350	.18	.23	.26	.33
	400	.30	.40	.48	.62
	450	.48	.67	.81	1.08
	500	.73	1.07	1.31	1.81
	550	1.07	1.62	2.04	2.90
	600	1.52			
	650	2.09			

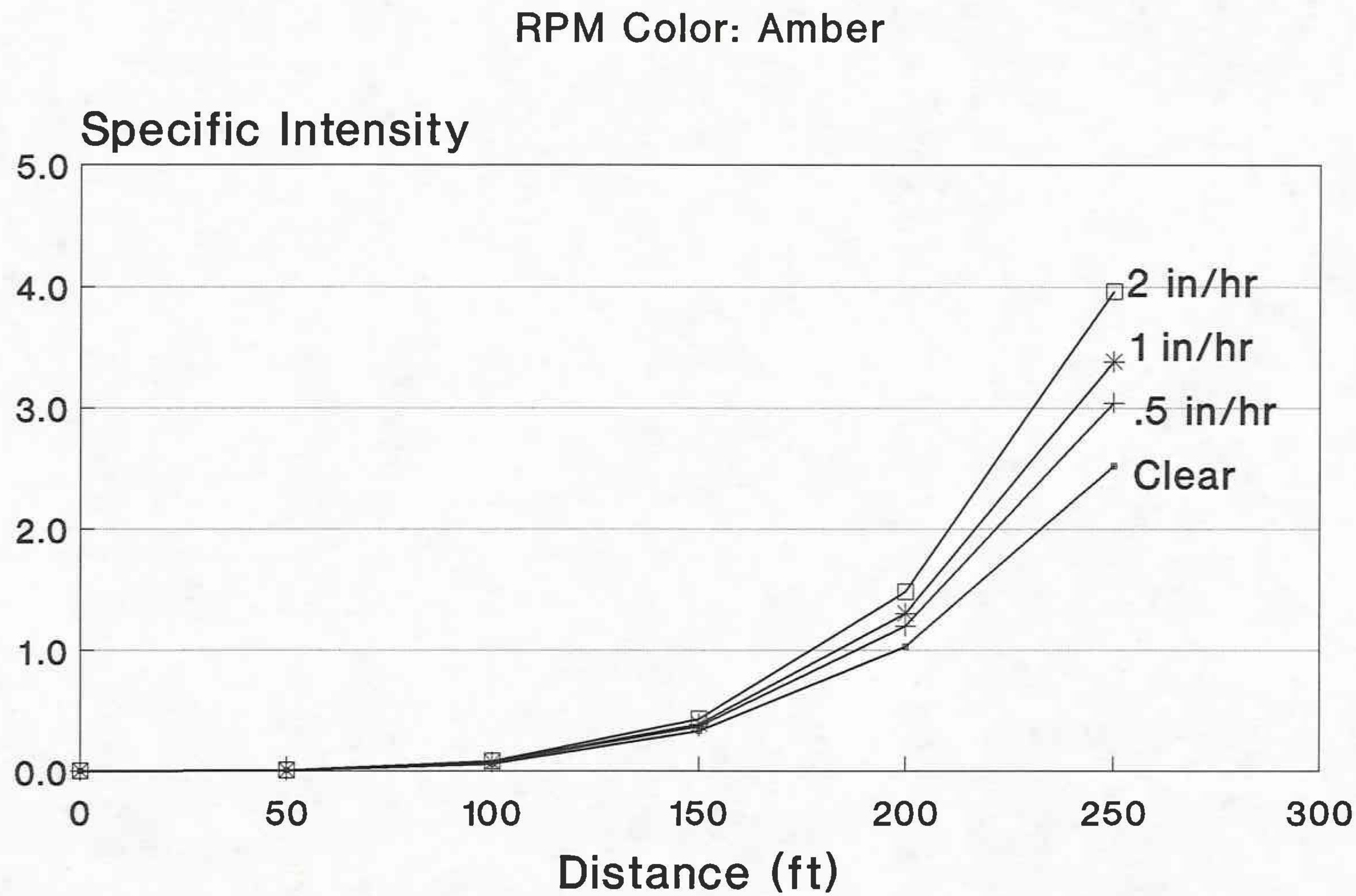

Figure 4-9. Predicted threshold SI.
Adapting conditions for observer:
Opposing traffic, wet pavement.

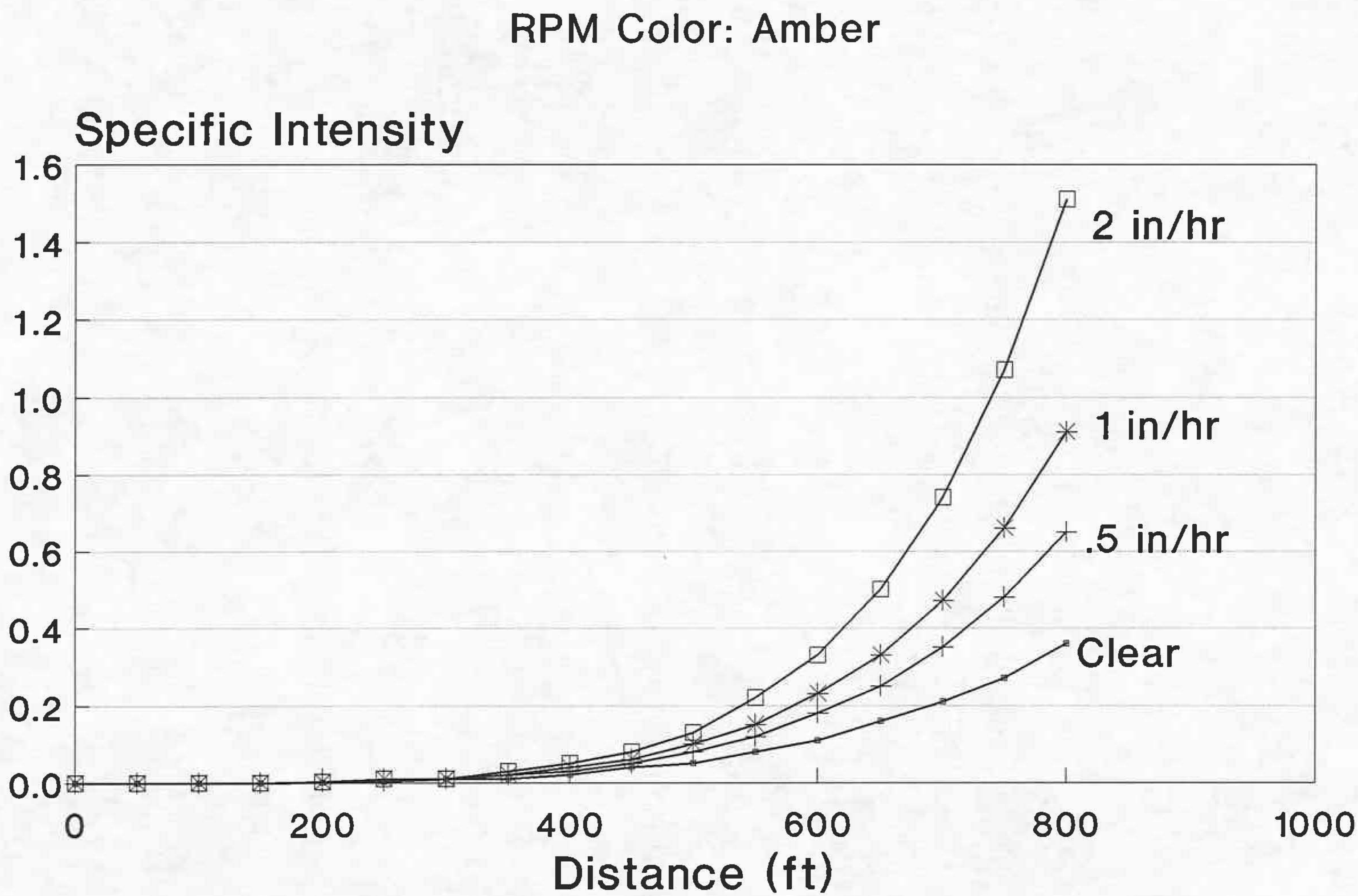

Figure 4-10. Predicted threshold SI. Adapting conditions for observer: Dark highway, No ambient lighting

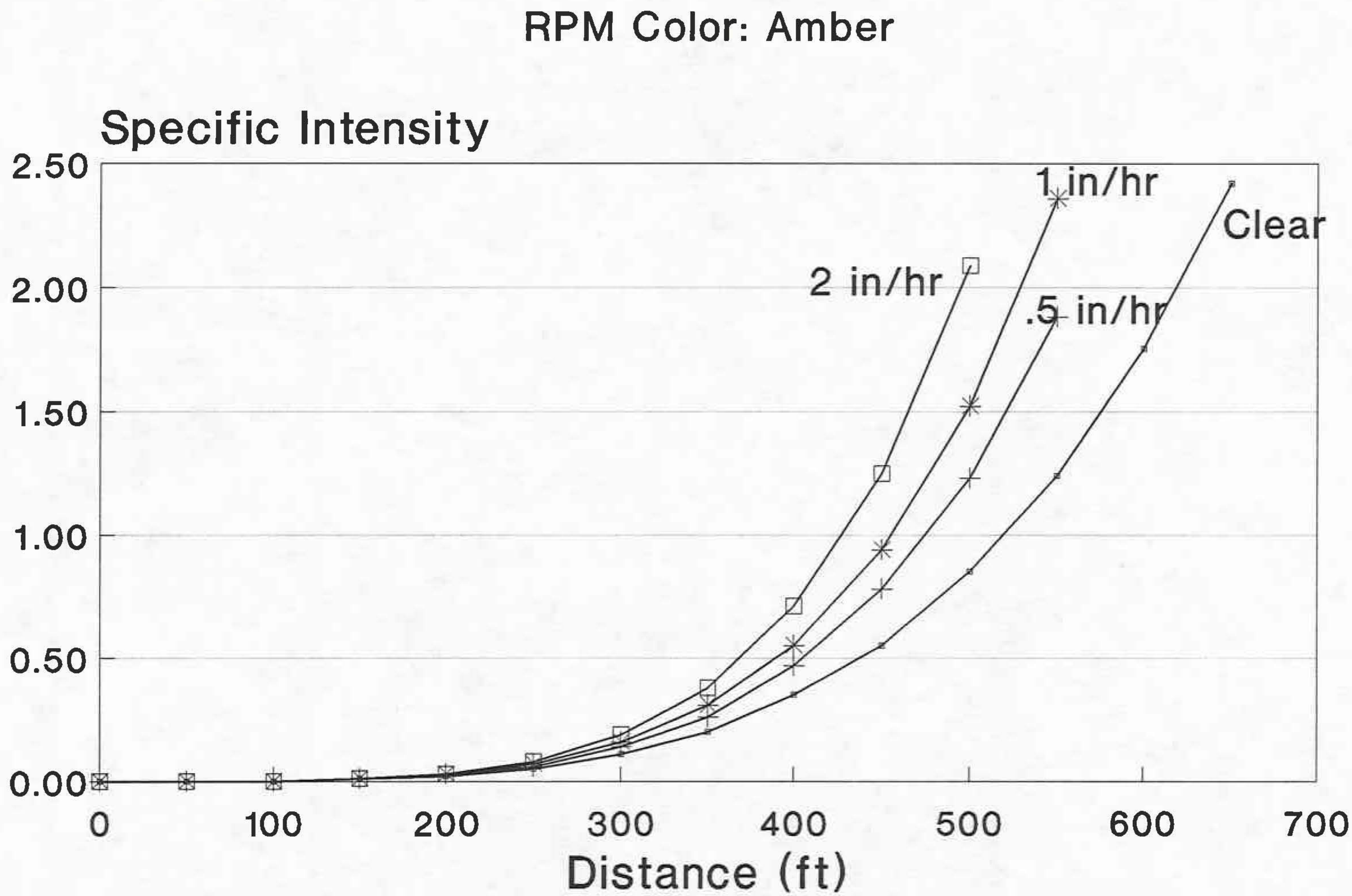

Figure 4-11. Predicted threshold SI.
Adapting conditions for observer: Urban
corridor, No opposing traffic

5. RAISED PAVEMENT MARKER DURABILITY

In order to provide effective path delineation over extended time periods, raised pavement markers installed on Texas highways must maintain a minimum level of retroreflectivity. The minimum specific intensities necessary for RPMs to effectively perform their function were discussed in Section 4. This section provides a brief discussion of the types of RPMs used on Texas highways and the materials used in fabricating these markers and reports the findings of a series of studies of some of the conditions that may mitigate against long term retention of sufficient retro-reflectivity. Among the abuses to which in-service RPMs are subjected are extremes of ambient temperature and repeated impacts from vehicular traffic. Three separate sets of studies are addressed in this section. The first is an assessment of the specific intensity of RPMs in several SDHPT districts after different periods of time in-service. Second, an account of two studies of the effect of thermal stress on RPM reflectivity is provided. Finally, the results of durability tests of RPMs when exposed to a laboratory abrasion test and to repeated tire impacts are reported.

Types of Pavement Markers Used in Texas

The vast majority of retroreflective raised pavement marker products used in Texas (by both the Highway Department and its contractors) are marketed under two trade names, <u>Stimsonite</u>, manufactured by a division of the Amerace Corporation and <u>Ray-O-Lite</u>, a division of Pac-Tec, Inc.

Both manufacturers make standard and low profile RPMs with reflective surfaces on one or both sides. Markers are available in a variety of reflective colors and color combinations, including amber(or yellow) clear ("crystal") and red. All of the markers are designed to reflect light back in the direction of the light source. This reflex- or retro-reflective property is accomplished by the incorporation of many small molded cube-corner (or prismatic) elements. In addition to size and color, the primary difference among RPMs lies in the treatment of the surface of the reflective element. The base surface of all markers is Methyl Methacrylate. On some Stimsonite markers, a thin layer of untempered glass is added to the RPM face. Table 5-1 provides a description of the primary RPMs used on Texas highways and employed in the empirical studies conducted under this project.

A preliminary comparative study of alternative materials for RPMs was conducted early in the research. This study consisted of library research plus interviews with cognizant individuals in the SDHPT, two major manufacturers of these devices (Amerace and FERRO), and Dow Chemicals in Freeport, Texas. As was mentioned in the preceding paragraph, the state-of-the-art in the manufacture of RPMs is the use of methyl methacrylate for the shell, which

Table 5-1. RPMs used on Texas highways.

Manufacturer	Model	Dimensions (in)	Reflective Area per side (in^2)	Surface Material
Ray-O-Lite	28	4.0x4.0x.70	≈ 3.25	Methyl Methacrylate
Ray-O-Lite	Mini	2.0x4.0x.45	≈ 1.87	Methyl Methacrylate
Stimsonite	88	4.0x4.0x.75	≈ 3.25	Methyl Methacrylate
Stimsonite	911	4.0x4.0x.75	≈ 3.25	Untempered Glass
Stimsonite	948	2.3x4.7x.52	≈ 1.87	Untempered Glass, recessed.
Stimsonite	947	2.3x4.7x.52	≈ 1.87	Untempered Glass
Stimsonite	74	2.3x4.7x.52	≈ 1.87	Methyl Methacrylate

includes the cube corner prism array. The interior of the shell in the area of the prism array is given a thin coating of aluminum as a reflective surface. Then the shell is filled with epoxy filler to produce the finished RPM. Stimsonite-made glass-faced RPMs are exactly the same as all-plastic RPMs, except a very thin glass surface is bonded by a patented process to the face of the prism array. The only way that water or any other contaminant can penetrate to the aluminum reflective layer to destroy the optical qualities of the device is outright cracking or breakage of the shell itself, provided the bond between the shell and filler is tight to begin with, a quality control problem in the past, but reportedly not a major problem now.

The major reason that methyl methacrylate thermoplastics are used to fabricate RPMs is their low cost and excellent performance under the wide extremes of heat and sun exposure to which these devices are subjected. In outdoor exposures, clear acrylics (the usual generic name for methyl methacrylate, since "Plexiglas" is a trade name) have experienced losses of less than 1 percent of their light transmission in 5 years. These plastics are universally used in aircraft windows. (Modern Plastics Encyclopedia, 1972-73). The only plastic that compares to acrylics in performance and durability for RPM use is the polycarbonate family. Polycarbonates, used very extensively for shells of power tools, sport helmets, space helmets and visors, and similar applications, have optical performance characteristics comparable (but not superior) to acrylics, but greater impact strength. The cost is roughly double that of acrylics. None of the persons contacted indicated that any plans exist among RPM manufacturers for substituting polycarbonate plastic for acrylics.

As the project progressed, it became apparent that the major problem with the optical qualities of RPMs with exposure was associated with abrasion of the surface of the optical array, as will be described in the paragraphs that follow. Hence the investigators decided to pursue this line of inquiry, and not further consider alternative materials for RPMs.

Assessment of In-Service RPMs

Among the first tasks undertaken for this project was an informal investigation of RPM experience and practices in several SDHPT Districts. Discussions with District Engineers and Maintenance Engineers in several of the Districts led to the collection of a small sample of in-service RPMs that were subsequently subjected to laboratory photometric analyses. The purpose of the measurements made on these RPMs was to provide a bench mark for the condition of RPMs that had been subjected to real-life operating conditions for known periods of time and to provide information pertinent to the life cycle of RPMs. Although several Districts provided RPM samples, the data presented here are based on RPMs provided by Districts 20 and 6, since those Districts provided specimens on the most regular basis.

Sets of seven amber Stimsonite Model 88 RPMs were removed from service on US Highway 89 in District 20 after 6, 9, and 12 months of service. The markers were selected randomly from areas with similar roadway geometry. The mean specific intensity of each set, measured after the markers were cleaned with a mild soap and water solution, and the nominal new SI of these markers are shown in Figure 5-1. This figure can be viewed as providing a "typical" life cycle for this model of marker on a rural, east Texas two-lane highway. Clearly evident in the figure is the dramatic drop in SI after only 6 months of service. Following 6 months of use, these RPMs retained an average of only 18% of their original specific intensity. The differences among the mean SIs after 6, 9 and 12 months are not statistically significant, suggesting that most of the performance decrements among these RPMs occur in a relatively short period of time, followed by a leveling off at a low SI level.

The specific intensity of the RPMs received from District 20 were measured under four conditions. In addition to determination of SI after the RPMs were cleaned and dried, as shown in Figure 5-1, each RPM was also evaluated:

As received, i.e. dry, but contaminated with dirt,
As received, but wet, and
After cleaning, wet.

Useful information is provided from the determination of SI under each of these conditions. The "as received - dry" measurement is consistent with the conditions under which RPMs are most often viewed on the road. This state, however, is not congruent with the

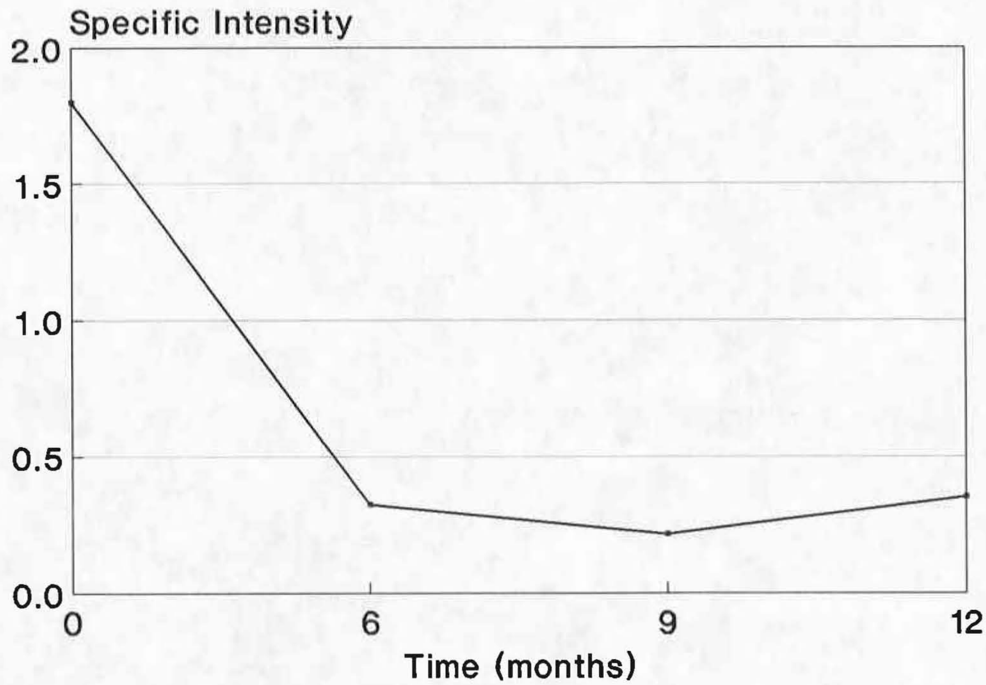

Figure 5-1. Typical RPM life cycle, plastic-faced Model 88.

conditions under which RPMs may be most useful for drivers, i.e., when visibility conditions are degraded. A critical need for RPMs is most likely to occur when it is raining, hence measurement of the markers "as received - wet." The "cleaned - dry" and "cleaned - wet" measures provide a means of evaluating changes in the physical status of RPMs without the confounding introduced by variable amounts of dirt buildup. Figure 5-2 illustrates the individual and average SI exhibited under each of these conditions for the seven 9-month-old Model 88 RPMs. The photometric performance of these RPMs, while variable, is quite poor under all measurement conditions except "cleaned - wet." It has often been observed that wet plastic-faced RPMs perform considerably better than the same RPMs dry. Inspection of Figure 5-2 shows this to be the case for this sample. The improvement, however, is striking only if the RPMs are relatively free of accumulated road dirt (i.e. "cleaned - wet"). RPMs measured wet, but not cleaned perform very similarly to the same RPMs that have been cleaned and dried (mean "cleaned-dry" SI = .217, mean "as received-wet" SI = .210). It has been suggested that although acrylic-faced RPMs are subject to abrasion from tire impacts, the reflectivity they lose from such abrasion is evident only under dry conditions where high levels are not critical. Based on this very small sample, it appears that the recovery of SI, presumably due to water filling the surface scratches, may be limited if the markers are not clean. Thus, while some improvement in the performance of plastic-faced markers may be

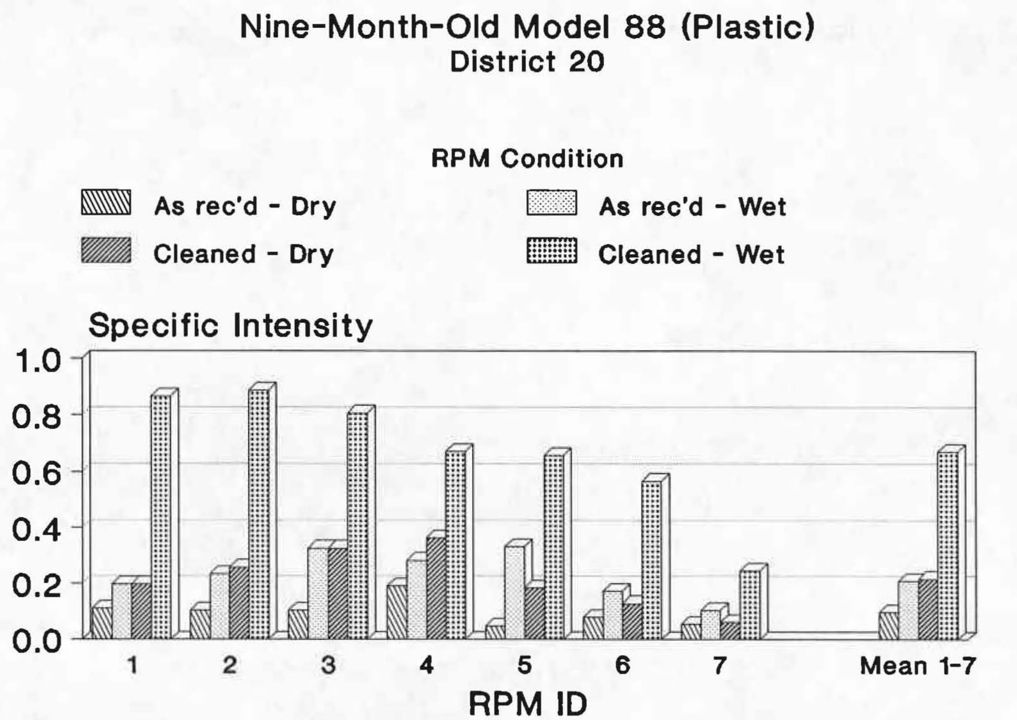

Figure 5-2. Dry and wet measurements of Model 88 RPMs.

anticipated under wet weather conditions, such improvement is likely to be minimal in areas where considerable environmental dirt is present.

A set of 11 glass-faced Model 911 RPMs removed from service in District 6 two years after installation showed much less evidence of degradation than the 9-month-old Model 88s (see Figure 5-3). Comparison of Figures 5-2 and 5-3 suggest that glass-faced markers may retain higher levels of SI under both wet and dry ambient conditions. The conditions to which these two sets of RPMs were exposed; including ambient temperatures, traffic volumes, and rainfall, are not known. It is important, therefore, to recognize that the superior SI retention of the glass-faced markers could be the result of exposure to less hostile conditions rather than an inherent superiority of those markers. These data are sufficiently suggestive, however, that empirical efforts, under controlled conditions, were carried out to determine if RPM surface material has a significant influence on the durability and SI retention of RPMs. The remainder of this section reports the methodology and results of those studies.

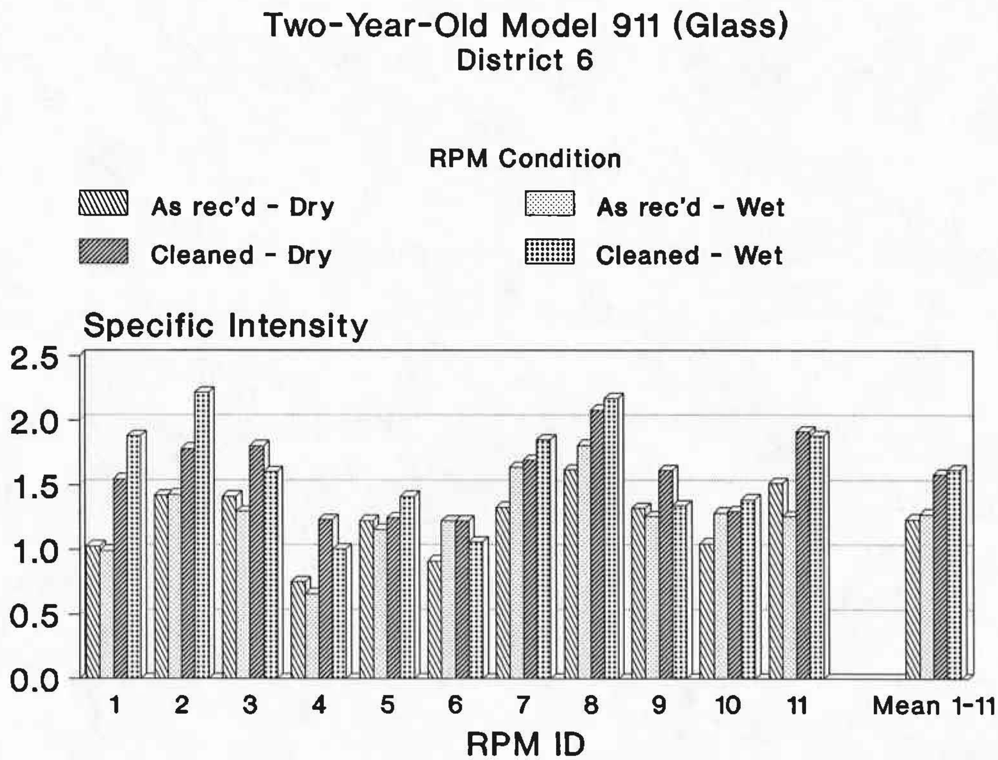

Figure 5-3. Dry and wet measurements of Model 911 RPMs.

Thermal Stress Study 1: The Effect of Thermal Stress on the Photometric Performance of Retroreflective Raised Pavement Markers

Introduction

Retroreflective raised pavement markers (RPMs) installed on Texas highways are subjected to a wide range of environmental conditions including large differences in ambient temperature in different geographical locations in the state, as well as substantial seasonal and day-night fluctuations. These ambient temperature differentials are magnified by the heat retaining characteristics of the asphaltic cement road surfaces to which RPMs are adhered.

Test Method Tex-846-B, "Method of Testing the Heat Resistance of Reflector Units", is implemented as part of the RPM acceptance testing conducted by D-9 of the State Department of Highways and Public Transportation. This test method calls for test specimens to be subjected to 140 degrees F for four hours. Test specimens whose photometric performance after heat treating, as measured by specific intensity, is less than 80% of the minimum specified performance prior to heating are considered to have experienced a substantial change in prismatic configuration.

Because the heat stresses to which installed RPMs are subjected are cyclical, a single test of heat resistance may not be adequate to characterize the effect of heat on RPM performance. In addition to being subjected to elevated temperatures, installed RPMs in some highway districts are exposed to low ambient temperatures. Therefore, a test of the effect of thermal stress arising from both high and low temperatures was conducted. One set of RPMs was subjected to repeated testing under the heat stress conditions specified in Test Method Tex-846-B. A second set of test specimens was exposed to an analogous procedure for low temperature in which RPMs were placed in a controlled cold environment. This set of RPMs was exposed to repeated cycles of 0 degrees F for four hours.

Method

Test Specimens

A total of 40 RPMs were tested, 20 in the "heat" test and 20 in the "cold" test. In each case, five new RPMs of each of four models were tested. The test sample comprised Stimsonite models 88, 911, and 948 and Ray-O-Lite Mini-markers. All test markers were reflective on two sides, thus providing 10 test surfaces of each type. The Stimsonite model 88 and Ray-O-Lite Mini-markers have plastic (methyl methacrylate) faces. Stimsonite models 911 and 948 have untempered glass covered faces. All RPMs used for this test are amber (yellow). Model 88 and 911 RPMs are standard

4 x 4 inch markers. Model 948 and Mini-markers are 2 x 4 inch "low profile" RPMs.

Test Procedure

The specific intensity (SI) of each test RPM was determined at the photometric laboratory at the Texas A&M Riverside Campus before heat treating. The entrance and observation angles for this and all subsequent SI measurements were 0 and 0.2 degrees, respectively.

The test markers in the "heat" set were subjected to eight cycles of heat treatment. In each cycle, the test specimens were exposed to 140 degrees F for four hours in a temperature controlled Precision Scientific convection oven. The SI of each reflective surface was determined after each heat cycle. In all cases, the RPMs were allowed to return to room temperature and were cleaned and dried before remeasurement. Markers in the "cold" set were tested in the same manner, except that they were exposed to only three cycles of cold treatment in a 0 degrees F cold vault for four hours.

Results

The influence of the hot and cold environments on RPM photometric performance are reported separately.

Heat Stress

The percent change (% Delta SI) from the pre-heat SI after each heat cycle was computed for each test RPM following each of the eight heat cycles. These data were subjected to a 4 (RPM type) x 8 (heat cycle) repeated measures analysis of variance, using the General Linear Models Procedure of SAS (SAS Institute Inc., 1988) to assess the influence of cyclical heat exposure on RPM photometric performance. The "percent change" data were used in the analysis, rather than absolute SI, to allow direct comparisons among the different RPM models. Substantial differences in initial photometric performance are observed among the various models due, in large part, to the inherent differences in the size of the retroreflective area.

The results of the analysis reveal a statistically significant effect on the amount of change in SI after heat-treating as a function of both RPM type, $F(3,36) = 114.9$, $p<.0001$, and heat cycle, $F(7,252) = 134.7$, $p<.0001$. Importantly, the interaction between RPM type and heat cycle is also significant, $F(21,252) = 37$, $p<.0001$.

This analysis clearly indicates that the effect of cyclical exposure to heat on RPMs is dependent on both the type of marker and the number of heat cycles. Table 5-2 shows the average percent

Table 5-2. Mean percent change in SI after heat-treating as a function of RPM type.

RPM Type	948	911	88	Mini
Mean % Change*	33.5	14.4	-10.7	-18.3

* All means differ significantly from each other, $p<.05$.

change in SI for each RPM type tested, collapsed over all heat cycles. Both of the glass-faced RPM models (models 948 and 911) exhibited an **improvement** in photometric performance after being subjected to heat. Conversely, the performance of both plastic-faced RPMs (model 88 and Mini-markers) declined. The most dramatic change is apparent among the model 948 markers which exhibited a nearly 34% average increase in SI when compared to before the heat cycles.

Average changes in SI resulting from each of the eight heat cycles are presented in Table 5-3, without regard to RPM model. These data indicate the somewhat erratic nature of the changes in RPM performance as a function of repeated heating. Note that the photometric performance does not appear to follow a simple increment or decrement until some asymptotic performance is realized. Rather, following each heat cycle performance may be better or worse than the preceding cycle. Averaged over all marker types, the best optical performance was obtained after seven heat cycles.

The clearest picture of the influence of the heat on RPMs is provided by the interaction of RPM type and heat cycle. Figure 5-4 graphically depicts the influence of each cycle on the average percent change in SI for each of the four RPM types. The observed differences between the performance of glass-faced (911 & 948) and

Table 5-3. Mean percent change in SI after heat-treating as a function of heat cycle.

Heat Cycle	7	8	2	3	6	5	4	1
Mean % Change	17.8	10.4	9.4	4.7	2.1	-1.2	-1.8	-3.6

Means underscored by a common line do not differ significantly, $p >.05$.

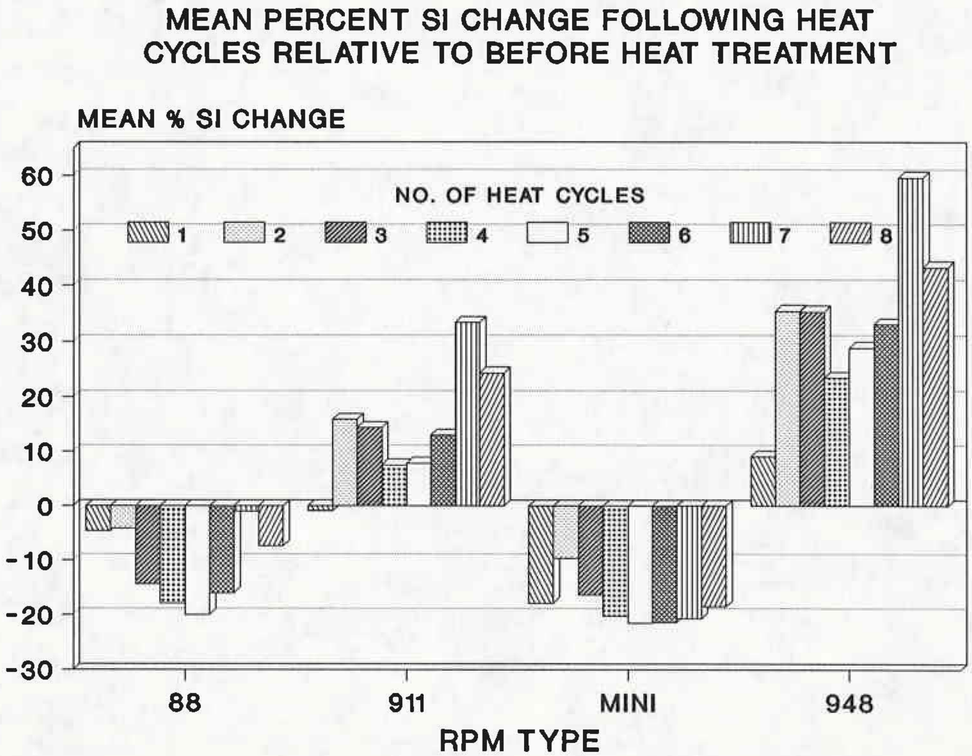

Figure 5-4. Change in SI as a function of RPM type and cycle

plastic (88 & Mini) RPMs following heat treatment are easily seen by inspection of the Figure. Also evident are the inconsistencies in RPM performance from cycle to cycle. Somewhat greater consistency between cycles was evidenced by the plastic-faced model 88 and Mini-markers than by the glass 911s and 948s. The **average** change in SI of the plastic RPMs, especially the Mini-markers, however, approached or exceeded the maximum performance degradation allowed by Test Method Tex-846-B.

Cold Stress

The absolute SI and the percent change in SI following each cold cycle are provided in Tables B-3 and B-4, respectively. The same type of analysis was performed on the cold stressed RPMs as reported above for the heated RPMs. The percent change data were subjected to a 4 (RPM type) x 3 (cold cycle) repeated measures analysis of variance to assess the influence of cyclical cold exposure on RPM photometric performance.

Like the previously reported analysis of heat treated RPMs, the results of this analysis indicate a statistically significant effect on the amount of change in SI after cold treatment as a function of cold cycle, $F(2,68) = 14.34$, $p<.0001$, and as result of the interaction between RPM type and cold cycle, $F(6,68) = 5.84$, $p<.0001$. Unlike the effect of heat, however, RPMs exposed to low temperature did not change differentially as a function of the main effect of RPM type, $F(3,34) = 1.23$, $p = 0.3123$.

The mean change in SI resulting from each of the three cold cycles, without regard to RPM type, are shown in Table 5-4. Overall, the first two cold cycles produced very small changes in SI. The final cold cycle did result in SI changes that, while still relatively modest, were significantly greater than that of the previous cycles.

The mean change in SI to each marker type, averaged over all three cold cycles, is shown in Table 5-5.

Table 5-4. Mean percent change in SI after cold-treating as a function of cold cycle.

Cold Cycle	1	2	3
Mean % Change	2.94	1.16	11.15

Means underscored by a common line do not differ significantly, p <.05.

Table 5-5. Mean percent change in SI after cold-treating as a function of RPM type.

RPM Type	948	911	88	Mini
Mean % Change	1.28	1.64	4.87	11.81

Means do not differ significantly, p >.31.

As was the case with the effect of heat on RPM performance, the graphical depiction of the significant cold cycle by RPM type interaction provides the clearest indication of the effect of repeated exposure to low temperatures. Inspection of Figure 5-5 demonstrates the relatively small effect of the cold treatment on all of the RPM types tested.

Discussion

The results of this study clearly demonstrate that repeated exposure to temperature extremes has differential effects on the optical performance of retroreflective RPMs. The explanation for the observed influence of high and low temperatures is less evident. Nonetheless, it appears that cyclic exposure to high ambient temperatures may contribute to reduced brightness of plastic-faced markers. The SI of glass-faced RPMs seems to improve with exposure to heat. Exposure to cold temperatures does not appear to have a substantial negative effect on either plastic or glass RPMs.

The temperatures to which the test RPMs were exposed are not outside the range that installed retroreflectors may experience. Considering that a hot mix asphaltic adhesive (Bitumen) is often used for adhering RPMs to the roadway, the 140 degree maximum temperature employed in this test may be lower than that which RPMs should withstand without significant change in performance. The bottom surface of RPMs are exposed to a thermal shock exceeding 350 degrees at the time of application. The relationship between that kind of short duration, but high intensity, thermal loading and the present longer exposure to lower temperatures is the subject of Thermal Stress Study 2.

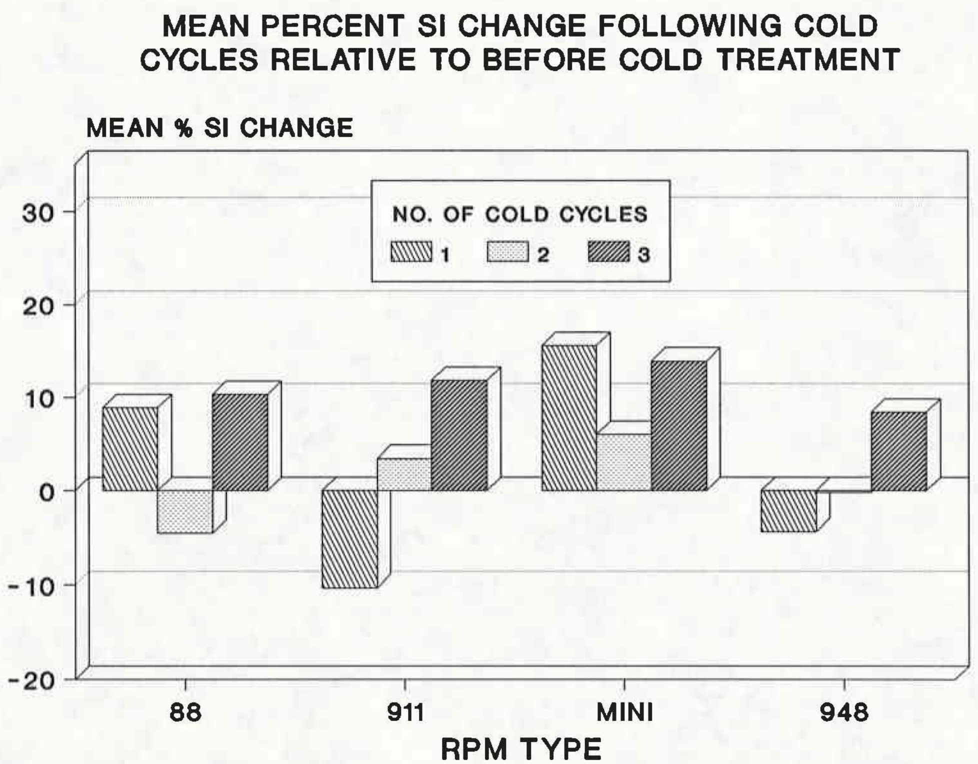

Figure 5-5. Change in SI as a function of RPM type and cycle

Thermal Stress Study 2: Thermal Shock from RPM Adhesive

Introduction

The results of Thermal Stress Study 1 raised the question of the effect, if any, on RPM specific intensity of thermal shock due to the heat applied to RPMs during installation. The bituminous adhesive used to affix RPMs to the road surface is heated to a temperature in the range of 350 to 400 degrees Fahrenheit. A pool of adhesive, at least as large as the base of the RPM, is placed on the road surface and the pavement marker is firmly positioned in the correct location.

In light of the results of Thermal Stress Study 1, several questions arise regarding the possible effects on RPM SI of exposure, albeit brief, to high temperatures during installation. Does the heat of installation affect the SI of RPMs? If there is a heat shock effect, does it affect the RPMs differently due to material (glass vs acrylic) or size (large vs small)? The present experiment was undertaken to answer these questions.

Method

Test Specimens

A random sample of four RPMs of each of four types was selected. The same RPM types used in Study 1 of this series were used here; i.e., Stimsonite Models 88, 911, and 948 and Ray-O-Lite Mini-markers. It will be recalled that the type 88 and Mini-markers are both acrylic-faced whereas the type 911 and 948 are glass-faced. Model 88 and 911 RPMs are standard 4 x 4 inch markers. The Mini-markers and Model 948 RPMs are both low profile. Each RPM has two reflective faces.

Test Procedure

The sample RPMs were cleaned and the specific intensity of each face was measured in the laboratory using the standard method described in Appendix A. These values were recorded and labeled "Pre-shock."

A quantity of bituminous adhesive was purchased from the District 17 SDHPT Office. The adhesive was heated to 360 degrees F. Pools of adhesive were poured on an asphalt concrete pavement surface and the test RPMs were pressed firmly in the hot adhesive in a random order. The air and pavement surface temperature at the time of installation was 75 degrees F. The RPMs were allowed to set for 20 hours. Low temperature during this time was 51 degrees F. After 20 hours, the markers were removed from the pavement and the specific intensity of each was remeasured in the laboratory. This provided the "Post-shock" measure.

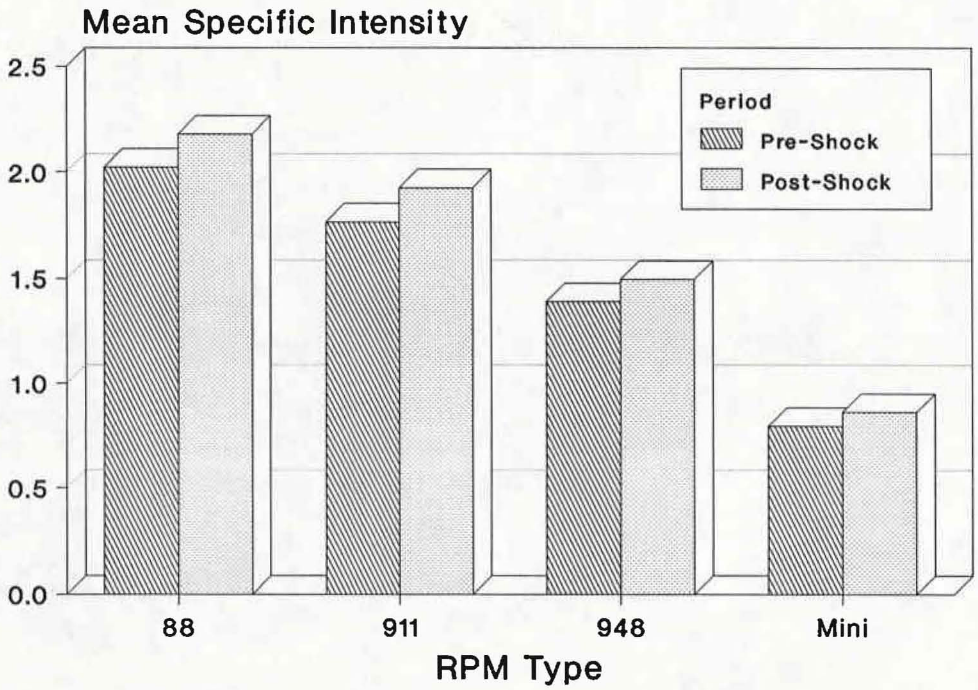

Figure 5-6. SI before and after thermal shock from adhesive

Results

The mean Pre-shock and Post-shock SI values for each RPM type are shown in Figure 5-6. These values were subjected to a repeated measures analysis of variance using the General Linear Model Procedure of SAS. Summary tables of this analysis are provided in Appendix B.

The analysis reveals significant differences among the mean SI values as a function of both period (Pre and Post) and RPM type ($p<.0001$). A small, but statistically significant <u>increase</u> in SI (from 1.49 to 1.62) was observed following exposure to the hot adhesive. The significant difference among RPM types was further evaluated using Tukey's Studentized Range (HSD) Test. The results of that test, summarized in Table 5-6, indicate that all four RPM types differed from one another. As expected, the larger RPMs exhibited higher SIs than the smaller, low profile RPMs. Although the interaction between period and RPM type is significant, examination of the mean SIs for each type and period reveals an increase on the order of only 7%-9% for each of the RPM types (see Table 5-7). These differences are rather small, particularly in comparison with the magnitude of differences in the percentage of change among the RPM types observed in Thermal Stress Study 1. Unlike the effect of exposure to the longer term lower temperature conditions comparable to environmental ambient temperatures, the heat shock resulting from application of RPM adhesive does not appear to have a detrimental effect on the SI of any of the RPM types tested.

Table 5-6. Tukey's Studentized Range (HSD) Test for variable: SI

Alpha= 0.05 df= 28 MSE= 0.001817
Critical Value of Studentized Range= 3.861
Minimum Significant Difference= 0.0412

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	TYPE
A	2.1012	16	88
B	1.8455	16	911
C	1.4438	16	948
D	0.8306	16	mini

Table 5-7. Specific intensity as a function of RPM type and period.

Type	Period	N	Mean SI	% Change From Pre to Post
88	pre	8	2.024	
88	post	8	2.179	7.66
911	pre	8	1.765	
911	post	8	1.926	9.12
948	pre	8	1.391	
948	post	8	1.497	7.62
Mini	pre	8	0.797	
Mini	post	8	0.864	8.41

Abrasion Studies

Newly installed retroreflective raised pavement markers (RPMs) provide reflection of vehicle headlamps at night far in excess of the visual detection thresholds of virtually all drivers under nearly all ambient conditions. Pavement marker retroreflectivity, however, has been observed to decline very rapidly. In some cases, as shown previously in Figure 5-1, RPM retroreflectivity falls to less than 20 percent of its initial value in as short as six months. While a number of factors contribute to the decline in RPM effectiveness, physical damage to both the clear protective surfaces of RPMs and to the retroreflective elements themselves appears to be a primary causative factor. A major source of this damage is repeated impacts by the tires of passing vehicles. Tires may break or chip reflectors and scratch the clear RPM surface. This abrasion is likely accelerated in areas where especially high concentrations of dirt, dust, and sand are commonly found in the highway environment.

Considerable anecdotal evidence has been offered concerning the relative merits of different types of RPMs in resisting physical damage. Two studies were undertaken to provide more objective information about the endurance of RPMs when subjected to physical abuse under controlled and repeatable conditions. In the first, RPMs were subjected to abrasion in the laboratory using a device that applies an abrasive material to the reflective surface of RPMs under constant pressure. The second study evaluated the effects of vehicle tire impacts on RPMs under controlled closed-course conditions.

Abrasion Study 1: Laboratory Abrasion of RPMs

In order to isolate the influence of abrasion on RPM reflectivity, whether resulting from environmental dirt, dust, sand, impacts from vehicle tires, or a combination of these factors, from other sources of RPM degradation, a laboratory test was devised that subjected RPMs to constant, controlled amounts of abrasion. This test used a specially designed "Abrasion Box" to expose RPMs to an abrasive surface with constant pressure.

Abrasion Box Design

A wooden box with fixtures that support and hold most varieties of retroreflective pavement markers was constructed. The **RPM holder** was constructed such that an RPM's reflective surface is positioned normal to the horizontal plane of the box. The **abrading element** consists of a free-floating block wrapped with foam padding that is covered with garnet cloth. The padding allows the abrasive garnet cloth to conform to any RPM surface irregularities, permitting optimal uniformity of abrasion. A lead weight is fixed on the top of the floating block. The entire abrading element is contained in a **sliding shelf** that allows movement of the abrading element over the specimen RPM. The abrading element and the complete abrasion box are shown in Figures 5-7 and 5-8, respectively.

Abrasion Procedure

The standard procedure for the abrasion of the pavement markers was as follows. The specific intensity of the specimen RPM is determined in the laboratory. It is then placed in the appropriate fixture in the abrasion box. A lead weight is placed on the abrading element such that a pressure of 1.25 psi is applied to the RPM. Because the retroreflective surfaces of different RPMs vary in area, different weights are needed to exert the standard 1.25 psi.

Once in place, the reflector is ready to be abraded. The shelf, containing the abrading element, is slid over the RPM. This constitutes one pass. Abraded RPM material collected in the garnet cloth is blown out every 5 passes for glass-faced RPMs and every 3 passes for plastic-faced markers. New garnet cloth is used for each test specimen.

After each pass for plastic and every 5 passes for glass RPMs, the reflector is removed, brushed lightly with a clean cloth, and then measured again to determine its SI. Typically, the procedure is repeated until the RPM's specific intensity is less than 5% of its original value.

Typical Results

Although numerous RPM samples have been abraded in the fixture described above, data from a single set of RPMs so abraded will serve to illustrate the typical findings.

Figure 5-9 depicts the change in SI of two glass-faced Model 911 RPMs and three plastic-faced Model 88s as a function of the number of abrader passes to which they were subjected. The SI of all three 88s was reduced to less than 0.5 by fewer than 20 abrader passes. In contrast, 20 passes produced some, but much less, SI decline in the 911s. Additional passes, in one case up to 100, resulted in no further decrement. The differences between plastic- and glass-faced RPMs in the laboratory abrasion test is illustrated further by inspection of Figures 5-10 and 5-11. These figures are photomicrographs of a Model 88 and Model 911 marker, respectively, after 10 abrasion passes. Comparison of the two pictures indicates the greater severity of the scratches on the Model 88 and, consequently, the greater masking of the cube corner reflective elements. In general, reflectors with plastic faces required only about 1\10 the number of abrading passes of their glass-faced counterparts to produce equivalent SIs. The Ray-O-Lite Mini markers, which have a plastic face the manufacturer describes as "hardened," proved slightly more resistant to abrasion than the other plastic-faced markers.

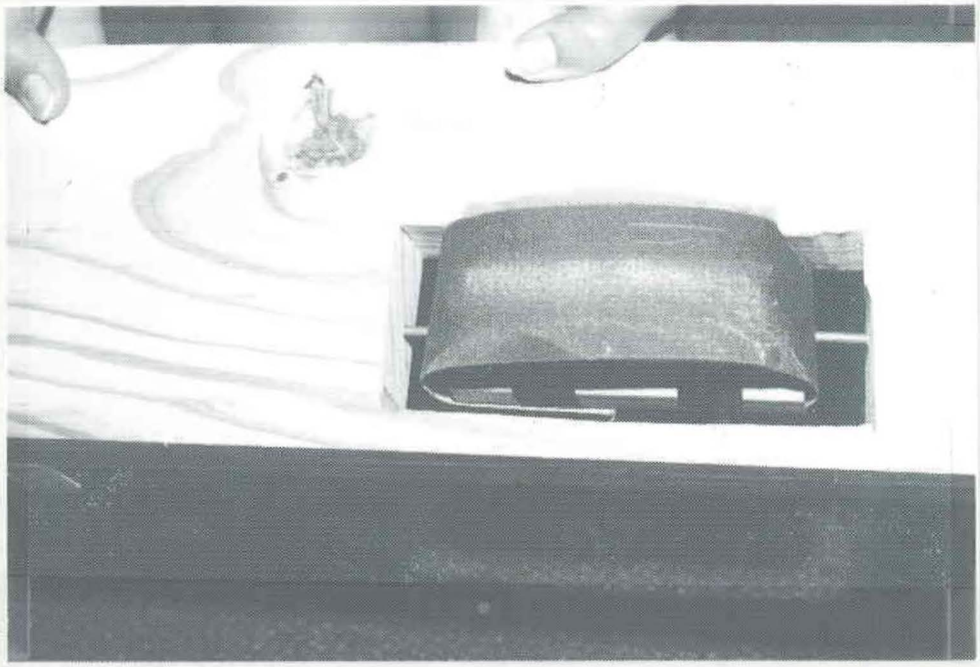

Figure 5-7. Photograph of abrading element of laboratory abrasion box.

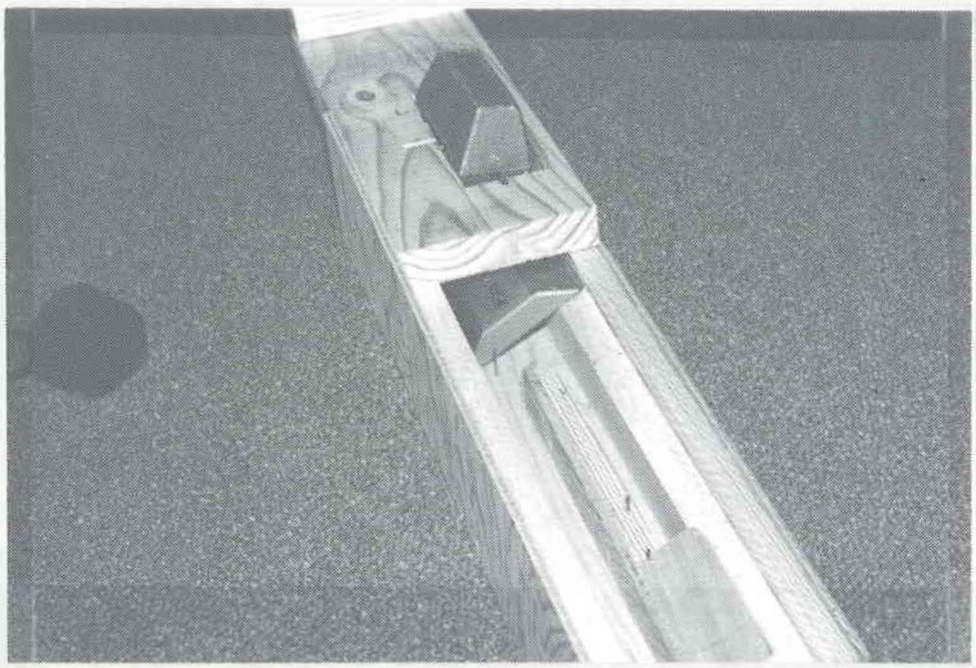

Figure 5-8. Photograph of laboratory RPM abrasion box.

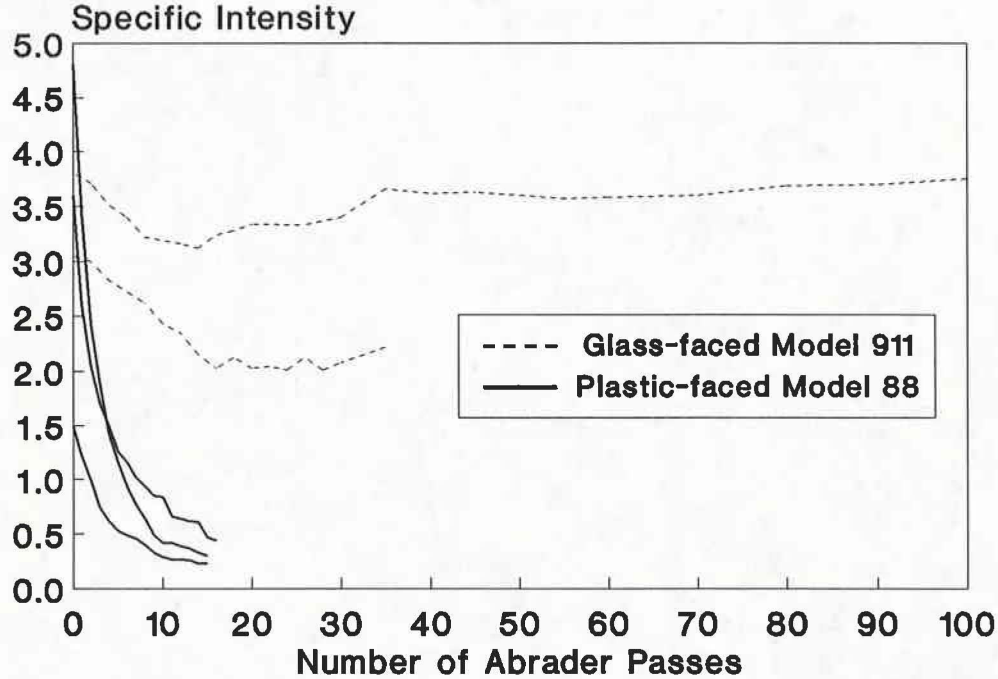

Figure 5-9. SI of laboratory-abraded glass and plastic RPMs

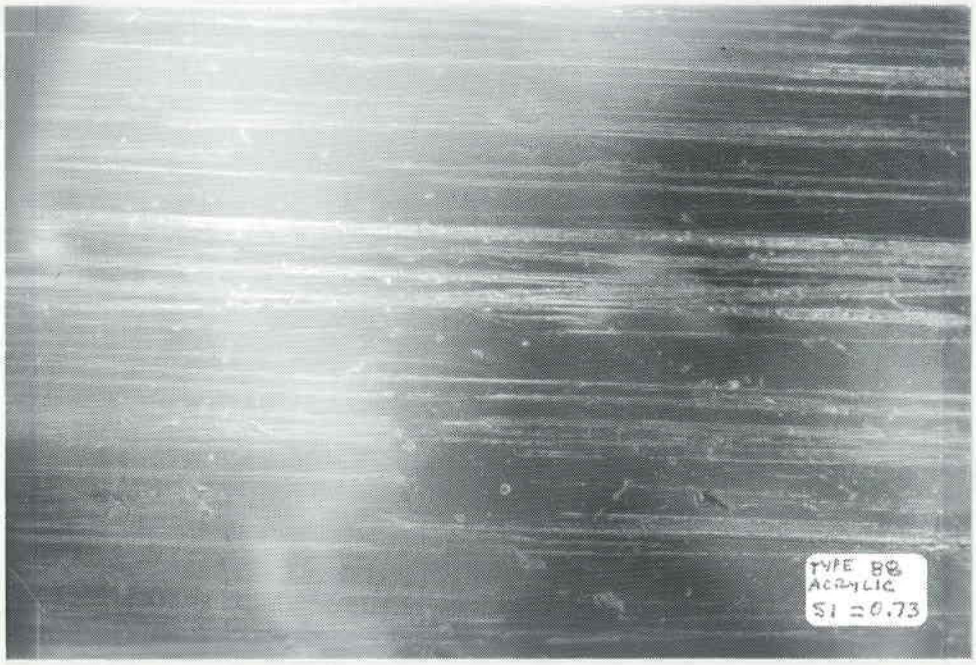

Figure 5-10. Photomicrograph of a plastic-faced Model 88 RPM subjected to 10 abrader passes.

Figure 5-11. Photomicrograph of a glass-faced Model 911 RPM subjected to 10 abrader passes.

Abrasion Study 2: The Effect of Tire Impacts on RPM Photometric Performance

This study was designed to provide information about the endurance of RPMs when subjected to physical abuse sustained from repeated tire impacts under controlled and repeatable simulated highway conditions.

Method

Test Specimens. A total of 28 RPMs (providing 56 retroreflective surfaces) were installed on an asphalt road surface on the runway complex at the Texas A&M Riverside Campus. The RPMs were applied by Texas SDHPT personnel using the hot-mixed bituminous adhesive typically used for RPM installation. Five or six new RPMs of each of five models were installed. The number and pertinent characteristics of the test specimens are provided in Table 5-8. The primary distinctions among the various RPM models tested lies in size, 2 x 4 inch low profile vs 4 x 4 inch RPMs, and in the exposed material on the marker face, acrylic vs glass.

Test Procedure. The specific intensity (SI) of each test RPM was determined in the laboratory before installation and on the test pavement before and after being subjected to tire impacts. Photometric measurements obtained after installation were accomplished using the Infrared Field Measurement Device (IRFMD), described in Section 3, that was developed as part of the RPM project.

Each test marker face was exposed to a total of 4400 tire impacts. Tire impacts were provided by driving a 1979 Pontiac Grand Am back and forth over the line of RPMs a total of 1100 round trips at approximately 40 mph. The test vehicle was equipped with steel belted radial tires maintained at the manufacturer's recommended pressure.

Table 5-8. Tire impact study test RPMs.

Number*	Manufacturer	Model	Size	Surface Material
6	Ray-O-Lite	28	4x4 in	Methyl Methacrylate
6	Stimsonite	88	4x4 in	Methyl Methacrylate
5	Stimsonite	911	4x4 in	Untempered Glass
5	Ray-O-Lite	Mini	2x4 in	Methyl Methacrylate
6	Stimsonite	948	2x4 in	Untempered Glass

*Each RPM has two retroreflective faces.

The test pavement and tire treads were kept relatively free, compared to actual highway conditions, of dirt, sand and small pebbles or other debris that might tend to accelerate RPM wear for the first 3600 impacts (900 vehicle passes). After 3600 tire impacts, an equal amount of dry blasting sand was poured over each RPM after every 50 vehicle passes to intentionally accelerate wear. Following a total of 3800 impacts, the sand was dampened, further increasing the abrasion introduced by tire impacts. All test RPMs were exposed to the same environmental conditions over the 5-month duration of the study, i.e., mostly hot, humid, sunny days, with occasional but infrequent exposure to rain.

The specific intensity of each reflective surface was measured after 1200, 2400, 3600, 3800, 4200, and 4400 tire impacts. Immediately before each SI measurement, the RPMs' reflective surface was cleaned with a commercial glass cleaner and a soft cloth to remove accumulated surface dirt. Periodic visual inspections of the markers were made and photographs were taken in addition to the photometric measurements.

Results

Photometric Measurements. Comparisons in durability among the RPM models were made on two measures: the absolute SI after tire impacts and the percent change in SI as a function of impacts. RPMs differ substantially in initial specific intensity, due both to individual marker differences and, especially, to the different retroreflective surface areas provided by standard and low profile markers. The percent change measure provides a convenient way to directly compare markers with different original characteristics. At the same time, analysis of absolute SI provides the opportunity to examine marker brightness in relation to threshold levels necessary for visibility on the highway. Both independent variables were analyzed by means of a series of analyses of variance (ANOVAs) to determine the influence of the number of tire impacts and type of RPM on marker durability. Although the number of tire impacts appears to be a continuous variable (from 0 to 4400 impacts), it is treated in the analyses as a discrete variable because of the intermittent addition of sand to the RPMs. Summary tables for all statistical analyses are provided in Appendix B as Tables B-4 and B-5.

The first analysis was conducted to determine the overall effect of tire impacts and RPM type on changes in SI. Originally, it was intended that the baseline for defining change in SI would be the pre-impact SI of each test RPM. Due to problems encountered with the field measurement system, the initial SI measurements were neither sufficiently valid nor reliable. The baseline for all comparisons, therefore, is RPM SI after 1200 impacts (300 vehicle passes). The percent SI change data were subjected to a 5(RPM type) x 6(level of impacts) repeated measures ANOVA using the General Linear Models Procedure of SAS (SAS Institute, 1988). The results of this analysis reveal a statistically significant effect on the percent change in SI after tire impacts as a function of both the number of impacts, $F(5,255) = 438.43$, $p < .0001$, and RPM type, $F(4,51) = 17.82$, $p < .0001$. The interaction between number of impacts and RPM type is also significant, $F(20,255) = 21.82$, $p < .0001$. This analysis indicates that the effect of tire impacts on the change in reflectivity of RPMs is dependent on both the number of impacts and RPM type.

Table 5-9 shows the average percent change in SI following the six levels of tire impacts, without regard to RPM type. Several points of interest are apparent in this table. First, overall reflectivity <u>increased</u> about 6% after 2400 impacts. This increase could be real, resulting from an initial polishing effect of the tires on the clean, new RPM faces. More likely, this apparent increase is an artifact arising from the inherent variability in the measurement of SI with the Infrared Field Measurement Device which was undergoing design modifications at the time these measurements were taken. Second, although statistically significant changes were observed through the first 3800 impacts, these changes are of little practical significance. Not until 4000 impacts did the average SI decrease to a point where subjective differences in visibility may be observed. It will be recalled that this point coincides with the addition of damp sand to the roadway to accelerate degradation.

The differential effect of tire impacts on different RPM types is shown in Table 5-10. Averaged over all levels of impacts, the RPM models tested all performed significantly different from each other. Notable in this table is the distinct difference observed between the two glass-faced RPM models and the three acrylic-faced markers. Also notable is the comparison within like-faced RPMs. Of the two glass-faced RPMs, the low profile 948 was less affected by tire impacts than the standard sized 911. Similarly, among the plastic-faced markers, the smaller "Mini" proved more durable than the two standard size markers.

Table 5-9. Average percent change in SI over all RPM models as a function of number of tire impacts (referenced to SI after 1200 impacts).

Impacts:	2400	3800	3600	4000	4200	4400
Mean % Change:	6.4	-3.7	-4.9	-28.7	-57.7	-61.4

Means underscored by a common line are not significantly different, $p > .05$.

Table 5-10. Average percent change in SI over all tire impacts as a function of RPM model.

	(Glass face)		(Plastic face)		
Model:	948	911	Mini	28	88
Mean % Change:	-6.6	-13.2	-29.9	-33.4	-40.6

The differences in marker durability discussed to this point have been all been relative to the markers' initial SI (to be precise, relative to SI after 1200 impacts). In order to assess the influence of tire impacts on the absolute SI of each marker type, an additional ANOVA was performed. In this analysis, the measure of RPM performance was absolute SI rather than change in SI. The results of this analysis again reveal significant differences due to the number of impacts, RPM type, and the interaction between these two variables.

The overall influence of the number of tire impacts on absolute SI is essentially the same as that for the percent change measure. That is, statistically significant, but small, reductions in SI are observed through the first 3800 impacts. Larger effects are evident after 4000 impacts (and the introduction of damp sand to the roadway). Substantial decrements in brightness are seen by 4200 impacts. Comparisons among the impact levels are shown in Table 5-11.

Averaged over all levels of impact, the mean SI of the standard size markers is greater than that of the low profile RPMs. For both standard (4 x 4 in) and low profile (2 x 4 in) markers, the glass-faced markers exhibit higher specific intensities than the plastic markers when exposed to tire impacts. These comparisons are evident in Table 5-12.

Table 5-11. Average SI over all RPM models as a function of number of tire impacts.

Impacts:	2400	1200	3800	3600	4000	4200	4400
Mean SI:	2.31	2.22	2.10	2.10	1.51	0.85	0.76

Means underscored by a common line are not significantly different, p>.05.

Table 5-12. Average SI over all tire impacts as a function of RPM model.

	(4x4 in RPMs)			(2x4 in RPMs)	
Model:	911	88	28	948	Mini
Mean SI:	2.37	1.95	1.80	1.24	1.12

Both analyses reported thus far reveal significant interactions between RPM type and number of impacts. These interactions are depicted graphically in Figures 5-12 and 5-13 for percent change and absolute SI, respectively. Evident in these figures is the differential effect of the level of tire impacts depending on RPM type.

Inspection of Figure 5-12 suggests that when RPMs are exposed to a relatively small number of tire impacts under clean roadway conditions, none of the RPM types tested changed very much. As the number of impacts increased, and the road conditions were made more conducive to abrasion by the introduction of sand, distinct differences are apparent as a function of RPM type. Specifically, performance of the glass-faced RPMs deteriorated at a much slower rate than the performance of the plastic-faced markers.

Figure 5-13 shows the effect of tire impacts on absolute SI as a function of RPM type. Initially, all of the 4 x 4 inch markers are brighter than the low profile 2 x 4 inch RPMs, irrespective of surface material. As the number of tire impacts and abrasiveness of the environment increase, however, the absolute brightness of the plastic markers decreases to a significantly lower level than that of the glass markers, regardless of size. This effect is most notable in the performance of the plastic Model 88 and the glass Model 948 markers. Early in the testing process, the 88s averaged the highest SI. At the end of testing, the 88s exhibited the poorest performance. This is contrasted with the 948s which were initially the least bright RPMs. Because they deteriorated less than any other RPM type, the average absolute SI of the 948s was second only to the Model 911s at the end of testing.

Visual and Photographic Inspection. In addition to the photometric measurements discussed above, the test RPMs were inspected and photographed periodically throughout the test period. Photomicrographs (40x) taken after testing was completed provided for closer examination of the RPM reflective surfaces.

Differences in the deterioration of the test RPMs resulting from repeated tire impacts was visually apparent for the various RPM types. In general, the plastic-faced RPMs evidenced a more

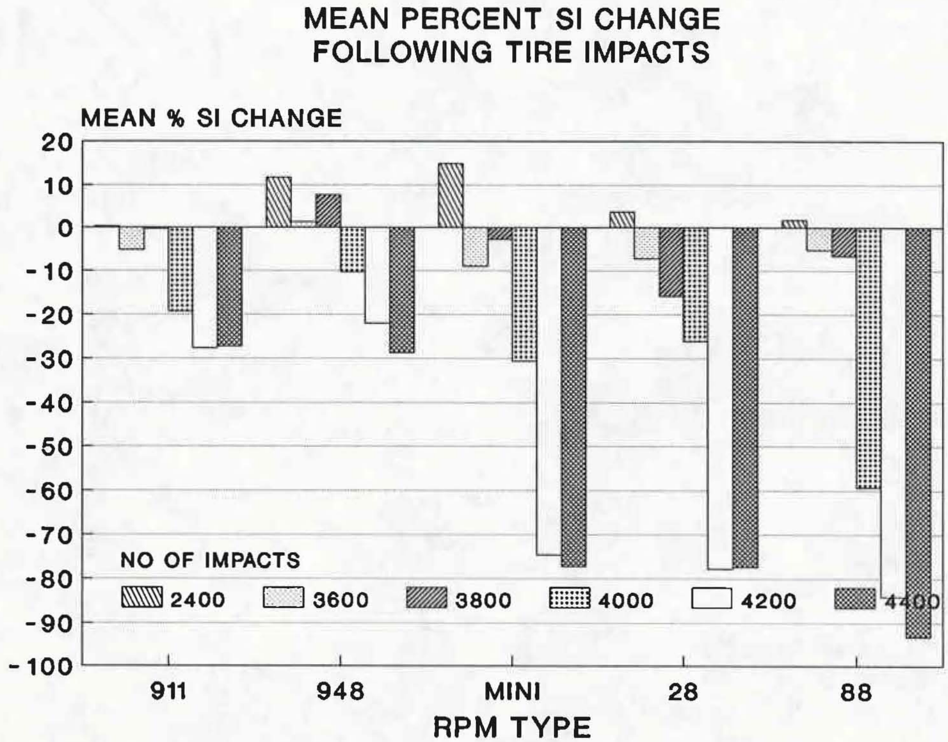

Fig. 5-12. SI % change as a function of RPM type and impacts

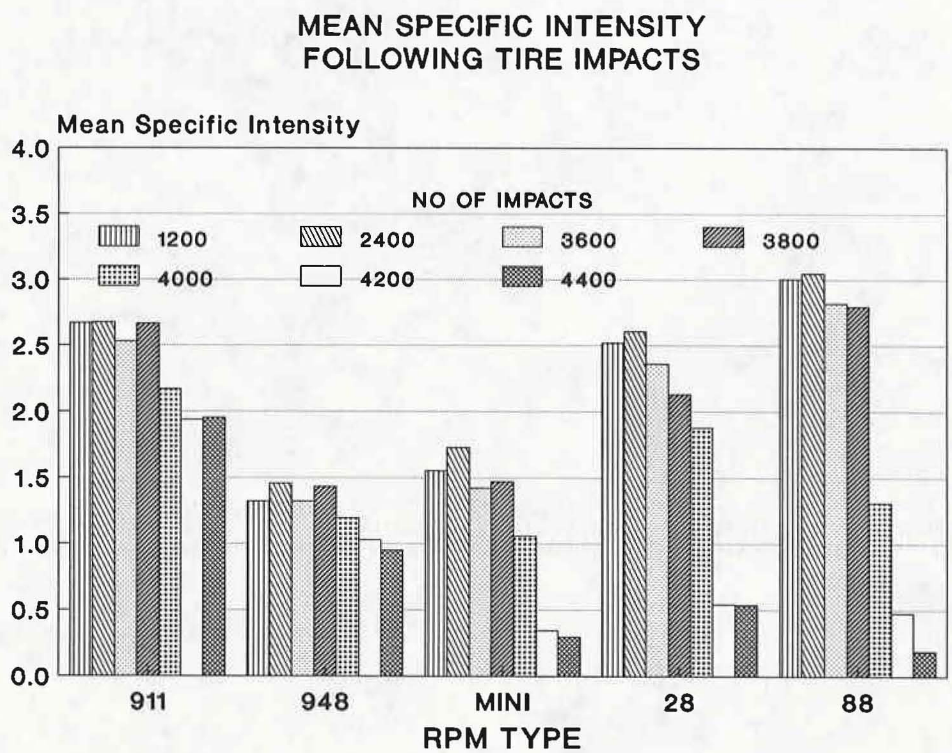

Figure 5-13. SI as a function of RPM type and impacts

uniform wear pattern than the glass markers. Under close examination with the unaided eye, this wear took on the appearance of a slight haze over the reflective surface. As illustrated in Figure 5-14, however, most of the plastic markers did not appear to be damaged to a great extent after 4400 impacts. Examination of the 40 power photomicrographs of the plastic RPMs reveals innumerable small scratches in an essentially random pattern. This abrasion pattern is evident in Figure 5-15. It is this abundance of scratches which result in the generally poor photometric performance of the plastic RPMs after repeated tire impacts.

Unlike the plastic RPMs, the glass markers reveal more obvious physical damage to the naked eye. Typically, pitting, chipping or cracking of the glass superstrate is evident along the top margin of the glass. This phenomenon, shown in Figure 5-16, is much more pronounced on the 4 x 4 inch Model 911 markers than on the low profile 948s. In addition, on a few of the larger glass markers, small pieces of the glass face were completely missing after testing. Viewed under 40 power magnification, the glass markers showed some evidence of the small scratches typical of the plastic-faced RPMs, but at a clearly much lower frequency. A typical photomicrograph of a glass RPM is provided as Figure 5-17. Whereas the scratches on the plastic faces were often sufficient to obscure the cube corner substrate, this was not the case with the glass markers.

CONCLUSIONS

Although glass markers evidenced more easily visible damage from tire impacts, the SI of these markers was shown to be better maintained under the accelerated wear conditions of the present endurance tests than that of plastic-faced RPMs. Larger RPMs, regardless of surface material, are initially brighter than smaller markers. Among the plastic RPMs tested, the superiority of the 4x4 RPMs was no longer evident at the conclusion of testing. Of the two glass-faced models, the larger markers remained significantly brighter than the low profile RPMs throughout testing. The average SI of the smaller markers, however, remained at an acceptable level throughout testing. In addition, these markers maintained a larger proportion of their new SI than did the larger markers.

The Standard Specifications (SDHPT, 1982) refer to Specification D-9-4200 for RPMs, which in turn invokes Test Method Tex-430-A "Method for Testing the Impact Resistance of Pavement Markers," as the sole test of durability of these devices. This is a test in which a 200 lb steel ball is dropped on a rubber-padded RPM from a height of 5 feet. All markers currently bought by SDHPT meet this specification. Based on the impact tests (using a motor vehicle) conducted in this research, no changes to Tex-430-A are indicated. The Department might consider an abrasion test patterned on the laboratory method described above to evaluate the other aspect of durability, wear and tear. The abrasion box is very

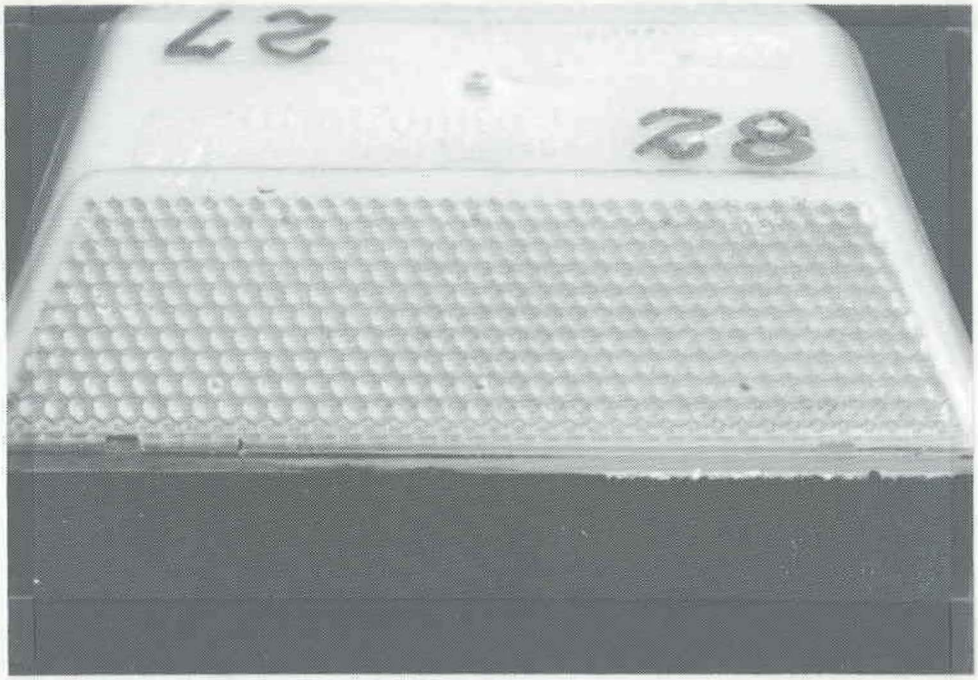

Figure 5-14. Photograph of plastic-faced Model 88 RPM (ID# 28) after 4400 tire impacts.

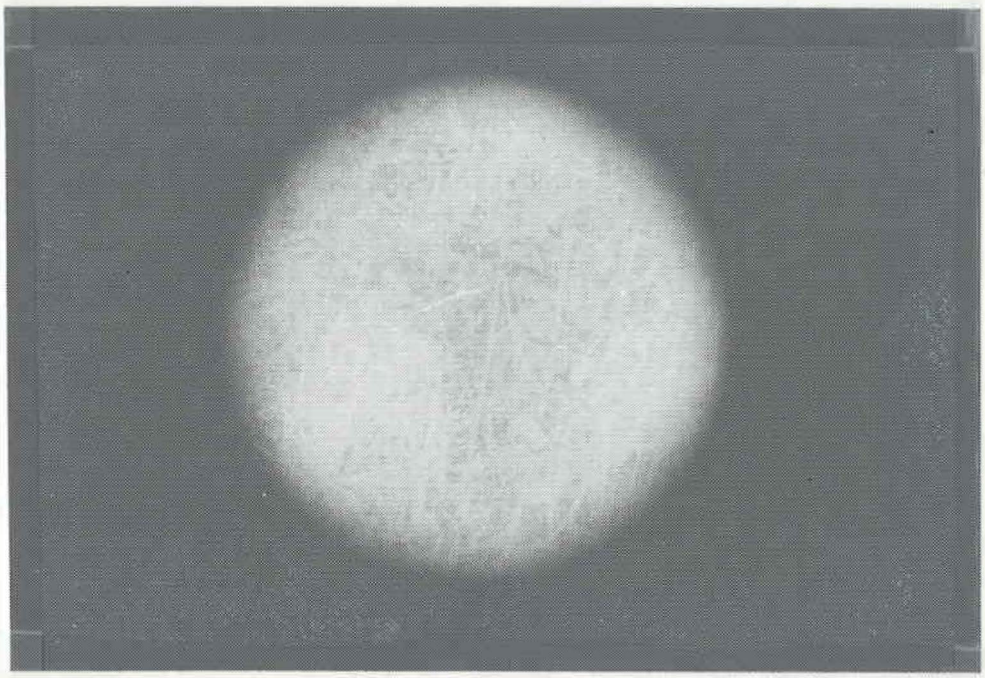

Figure 5-15. Photomicrograph of plastic-faced Model 88 RPM (ID# 28) after 4400 tire impacts.

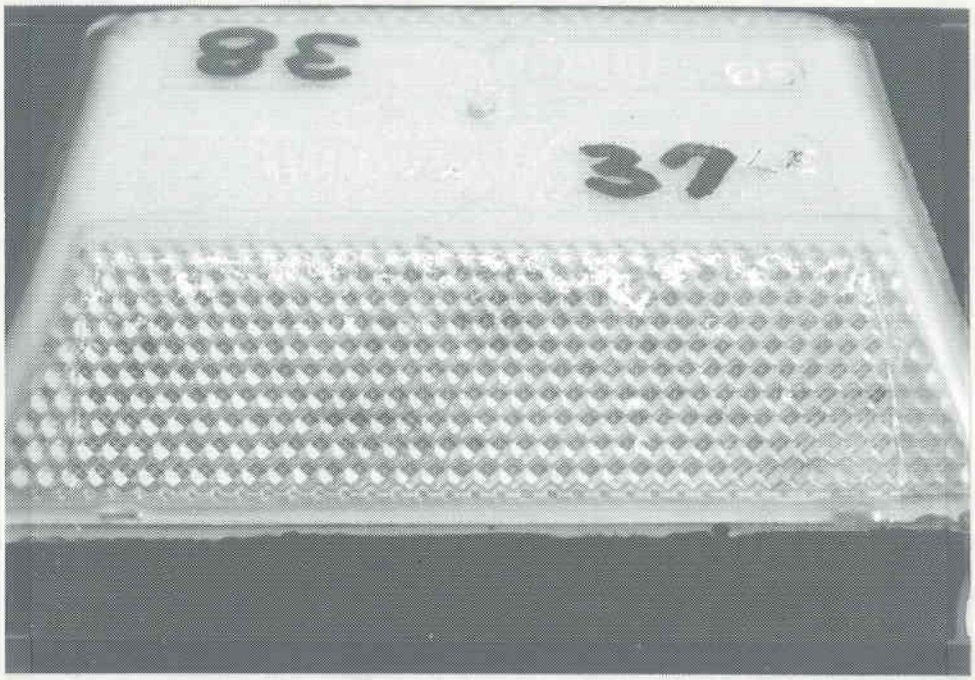

Figure 5-16. Photograph of glass-faced Model 911 RPM (ID# 37) after 4400 tire impacts.

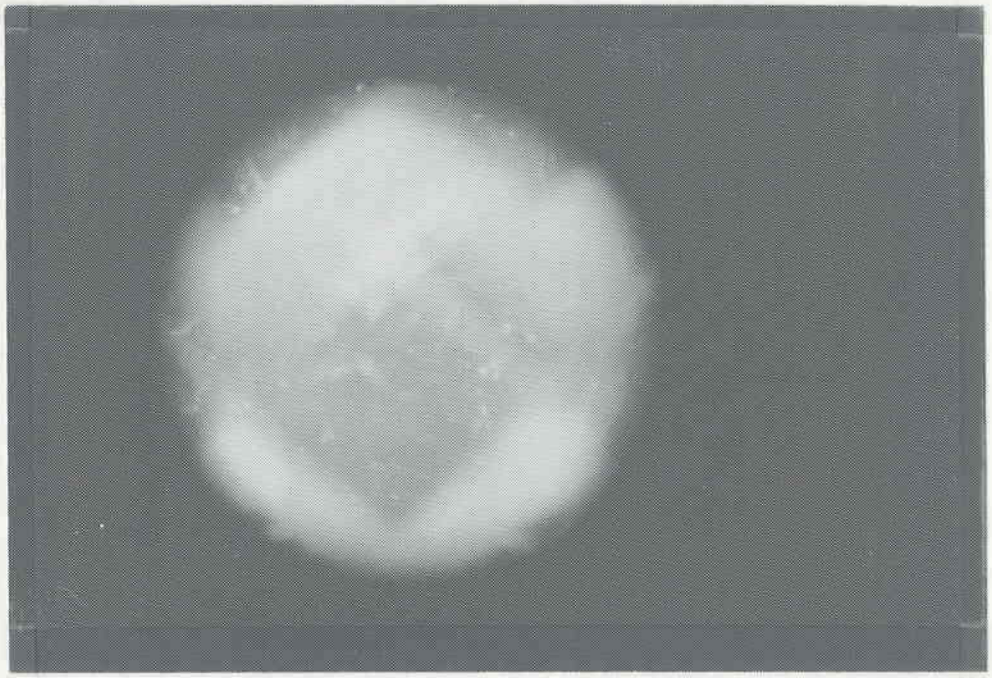

Figure 5-17. Photomicrograph of glass-faced Model 911 RPM (ID# 37) after 4400 tire impacts.

simple to make. Alternatively, the actual run-over test protocol could be adopted for a durability test. The latter test, however, is labor-intensive, and probably not practicable on a continuing inspection basis.

Based on the results of the present testing, it is reasonable to expect that under actual highway conditions, glass-faced RPMs will experience less change in photometric performance and subsequently less subjective loss of brightness over extended exposure to tire impacts than like-sized plastic markers. Differences will be especially pronounced where the environment is particularly dusty or sandy and at RPM installations especially prone to tire impact. These likely include installations on high volume roadway segments with horizontal curves, passing zones, and narrow lane width highways.

6. FEASIBILITY OF RPM RESTORATION

It has been shown that cleaning the accumulated dirt and road grime from the reflective surfaces of RPMs significantly improves their specific intensity. It has been further demonstrated that abraded RPMs, particularly plastic-faced markers, exhibit higher SIs when they are wet than when they are dry (see, for example, Figure 5-2). Presumably, water serves to fill the myriad small scratches and, at least partially and temporarily, restore the integrity of the surface. Discussions of this phenomenon among project staff led to attempts to more permanently restore the surface of damaged RPMs.

To this end, selected abraded RPMs that were used in the study of the effects of tire impacts on RPM photometric performance (reported in Section 5) were treated with a clear acrylic spray. Both plastic- and glass-faced markers were treated. The initial results of the informal experimentation with the degraded markers were sufficiently promising to warrant additional, more controlled, study of the feasibility of restoring the reflectivity of plastic-faced RPMs.

Method

Eight Model 88 RPMs were selected at random from our stock of pavement markers to serve as test specimens. The specific intensity of both reflective faces of each marker was measured using the standard method described elsewhere. One face was selected at random from each marker to be the test specimen. The selected face was abraded using garnet cloth until the SI was less than 10% of its original value. At this point, the markers were divided into two treatment groups. One group was treated by spraying the abraded face with a clear acrylic (Krylon, No.1303, Crystal Clear). The other group was treated by coating the face with a clear epoxy (Hardman, Double/Bubble, No. 04001).

Treatment of the "acrylic" group was accomplished by spraying the abraded face from a distance of 3 to 5 inches until the surface was completely coated and the coating just began to puddle. The epoxy used on the second group was a two-part epoxy. After thoroughly mixing the resin and hardener, the mixture was applied to the surface of the test RPMs with a 3 x 5 inch index card until smooth.

A discussion with a technical representative of Borden, Inc., manufacturer of Krylon brand spray coatings, suggested that the acrylic spray coating would deteriorate rapidly in the face of moisture. If RPM restoration is to be practical, it is necessary that any improvements in SI realized from the treatments can be maintained in the operational environment. Therefore, two brief tests of the durability of the restored RPMs were undertaken.

Following restoration, all test specimens were subjected to 14 days of weather and then to a series of tire impacts.

During the weathering period, conducted in December, RPMs were subjected to both freezing temperatures and rain. Air temperature ranged from a low of 2 degrees F to a high of 73 degrees. Measurable rainfall occurred on 5 days of the 14-day test.

For the tire impact test, the RPMs were installed on the same pavement surface used in the previously reported impact test. This test comprised 400 impacts under the same conditions as the "clean" impacts of the earlier test.

The SI of each marker was determined in the laboratory when new and after each experimental treatment, providing a total of five SI evaluations of each RPM as follows:

1. New
2. After abrasion
3. After restoration treatment (acrylic or epoxy)
4. After weathering
5. After tire impacts

Results and Discussion

The average SI of the "acrylic" and "epoxy" RPM groups for each evaluation period are provided in Table 6-1. Also indicated in the table is the average percent of the new SI value obtained at each measurement. The average SI of the abraded faces is on the order of 5% of the original value. After restoration, both the acrylic and epoxy treated RPMs showed improvement in SI. The small difference between the two restoration materials is not statistically significant ($t = .702$, $df=6$, $p > .51$). Restoration, by either method, more than doubled the SI of the markers. On a percentage basis, this is an impressive improvement. In absolute terms, however, the average SI of all restored markers was only 0.296. Figure 6-1 depicts the average change in SI from new-to-

Table 6-1. Mean specific intensity of restoration test RPMs.

Measurement Period	"Acrylic" Mean SI	"Acrylic" % Of New	"Epoxy" Mean SI	"Epoxy" % Of New
New	2.020	-	2.036	-
After abrasion	0.102	5.0	0.141	6.9
After restoration	0.266	13.2	0.326	16.0
After weathering	0.248	12.3	0.280	13.8
After tire impacts	0.282	14.0	0.278	13.7

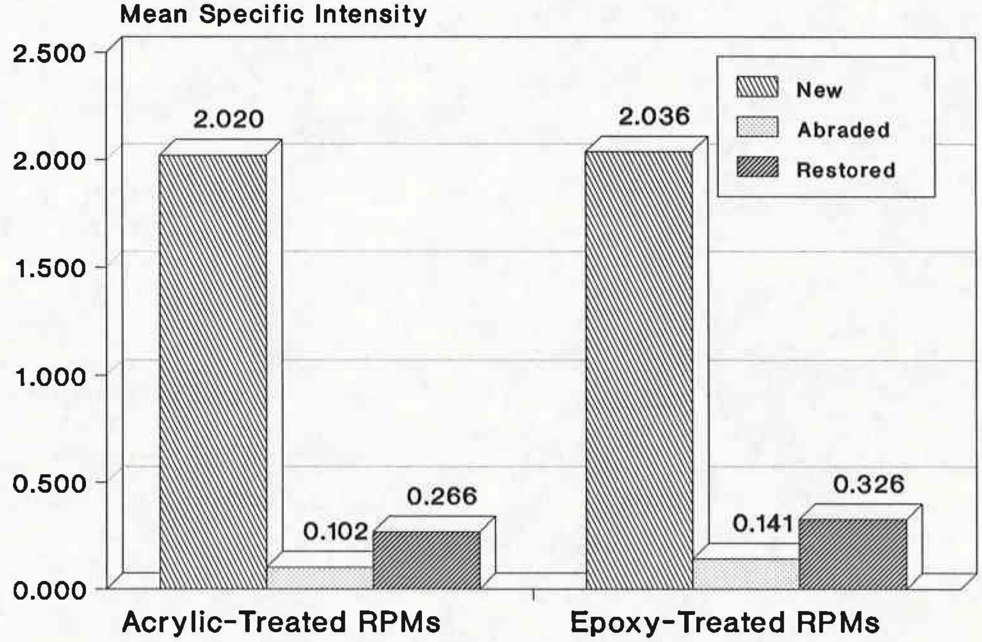

Figure 6-1. SI of new, abraded, and restored Model 88 RPMs.

abraded-to-restored. As is evident in Figure 6-1, although both restoration methods resulted in greater than 100% improvement in the SI of severely degraded markers, the restored RPMs exhibited specific intensities of only about 15 percent of their original new values.

The limited weathering and tire impact tests conducted with the restored RPMs produced little change in marker brightness. The minor differences, apparent in Table 6-1 and Figure 6-2, between the restored SI values and those values after weathering and tire impacts, suggests restored RPMs could withstand at least short-term exposure to operating conditions.

The present restoration study was not exhaustive in either the materials used or application techniques. Nor did this effort consider the cost-effectiveness of restoration. It is conceivable that other coating materials or application methods might provide a higher degree of rejuvenation. Any additional efforts in that regard should consider methods that can be adapted to mass application of the restorative to in-service RPMs. If an effective material is found that can be applied practically, a cost-effectiveness study must be undertaken to assure that the costs associated with restoration do not exceed the costs of purchasing and installing replacement markers.

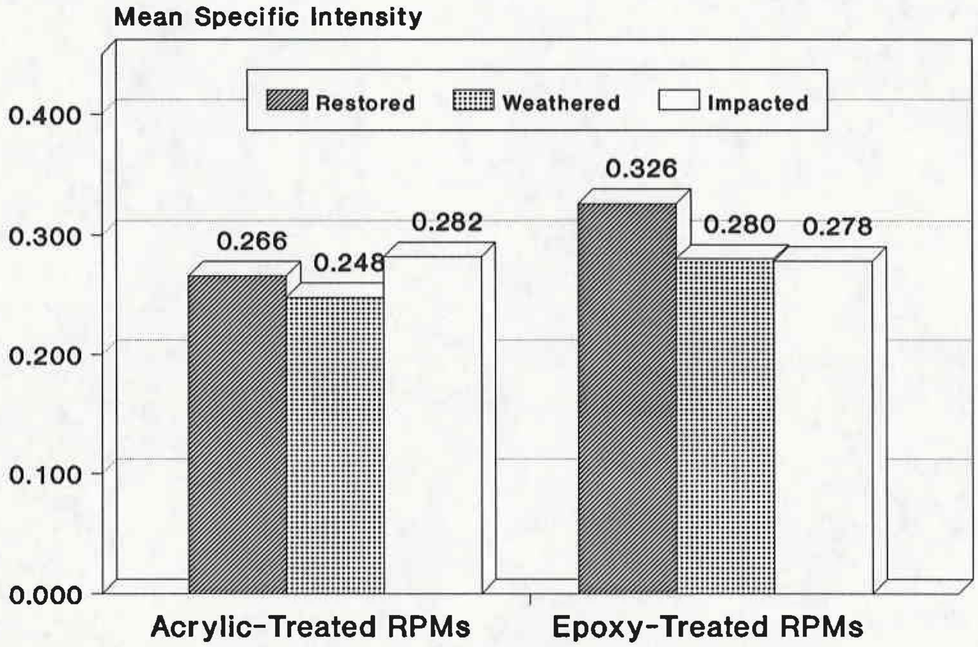

Figure 6-2. SI of weathered and tire impacted restored RPMs

7. RAISED RETROREFLECTIVE PAVEMENT MARKER PURCHASING TRENDS IN OTHER STATES

In response to a query from the project technical monitor, an informal telephone survey of other state practices and experience with retroreflective raised pavement markers was conducted. After some preliminary study, three states with similar climates to Texas and with flexibility in purchasing practices were contacted. These states were California, Florida, and Georgia.

California

The contact in California was Mr. Earl Shirley, chief of the Division of New Technology and Research for CalDOT. Except for the High Sierras and other locations in which snow clearance is a big factor, all parts of California use glass-faced Stimsonite RPMs. In the past these have been Model 911 units, but practice in recent years has been to purchase nothing but the low profile Model 948. California has had problems with RPM adhesives in the past, but not since moving to bituminous compounds. TTI research (Tielking and Noel, 1988) was instrumental in making the switch to these adhesives. The 948s have performed very well for CalDOT, according to Mr. Shirley.

Florida

Mr. Charles Peoples and Dr. Raymer of the Materials and Research Engineer Office in Gainesville were the contacts. Florida is very eclectic in their purchase of retroreflective RPMs. They buy Stimsonite Model 88 plastic-faced units for "temporary" use on surfaces that will soon be resurfaced. They also buy Ray-O-Lite Model 28 RPMs for similar usage. Florida refers to such devices as Class A. The preference is to use the more expensive but much more long-lived glass-faced Stimsonite Model 911 and 948, which Florida designates Class B. Florida experienced some problems in 1988 with 911 markers breaking up or cracking after a short period of use, due, apparently, to a quality control problem in Stimsonite, but have had no trouble recently. Model 911 predominates in installations in Florida, with 948s a close second. Some Caliguide octagonal units are also used in certain applications with good results. Like California, the change to bituminous adhesives (especially for 948s) has alleviated the marker loss problem.

Georgia

Mr. Gerry Gossett of the Materials and Research Division of Georgia Highways reported that his state uses Stimsonite Model 948 exclusively. In 1989 Georgia will have over 2 million in service, with an annual replacement ratio of 1:4 (500,000 per year). Georgia has tested a number of other devices and settled on the Model 948, which they consider to have an average life of 2 years. Georgia uses a method of measuring SI which was devised by

Stimsonite. The method involves a 10-foot tube and 0 degree entrance angle. The measure thus made may or may not be equivalent to the ASTM or SAE method. Using their method, Georgia considers an RPM to be below an acceptable range when its SI is less than 0.5 candela per incident foot-candle, a very conservative criterion. They have had no problems with the 948s since turning to bituminous adhesives for installation, with 98 percent retention on asphalt and 95 percent on concrete road surfaces.

8. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Measurement Technologies

1. Established procedures for measurement of the specific intensity of small, effectively point source, retroreflectors found in both Society of Automotive Engineers and American Society for Testing and Materials recommended practices yield measurements that are at variance with State Department of Highways and Public Transportation Test Method Tex 842-B by a factor of pi (3.1416). Other states have different measurement procedures, derived from manufacturer recommendations, which also yield different results. Although States use different methods for measuring the retroreflectivity of raised pavement markers, two national standards exist: ASTM E 809-81 Standard Practice for Measuring Photometric Characteristics of Retroreflectors and SAE Standard J594f - Reflex Reflectors.

2. A method for measuring raised pavement marker retroreflectivity in place, i.e., installed on the highway, was developed. This vehicle-installed system uses an externally mounted infrared source and receiver, with an in-vehicle logic circuit, display and recorder. The system can be used at highway speeds, but as currently configured requires running the vehicle tires over the RPMs measured to assure accurate aiming. Multiple passes over a string of markers are necessary to assure accuracy of measurement. The system records directly in specific intensity.

Driver Visual Thresholds

1. There is no one value for minimum specific intensity that can be specified independent of required sight distance, roadway geometrics and traffic conditions. A marker which may be perfectly visible on a dark night on a highway without opposing traffic headlamps may become completely invisible to even the youngest, keenest-sighted driver under urban conditions with a lot of glare. Older drivers may have great difficulty seeing even brand new RPMs under seeing conditions they routinely encounter in city traffic. Sight distances also differ for amber, red, and crystal retroreflectors. Threshold detection of amber RPMs (as a point of light, not necessarily identifiable as amber per se) requires lower specific intensity than either red or crystal. Tabled values of threshold SI for various conditions of weather, sight distance, and opposing traffic provide RPM SI levels at which replacement should be considered.

2. From a driver perception standpoint, it makes no difference whether an RPM is damaged, but the remaining part is still retroreflective, or an RPM is intact, but its surface

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2. From a driver perception standpoint, it makes no difference whether an RPM is damaged, but the remaining part is still retroreflective, or an RPM is intact, but its surface

degraded, if the light delivered to the eyes is the same. Just because an RPM face is damaged, it does not necessarily have to be replaced. The SI may still be within acceptable limits. However, if breakage extends through the plastic prism layer to the aluminum coating, moisture will probably detach or corrode the coating. Such an RPM will soon lose all retroreflectivity and should be replaced.

Raised Pavement Marker Durability

1. Studies of otherwise comparable glass- and plastic-faced RPMs removed from service after known amounts of exposure to highway conditions show a significant superiority in remaining SI for glass-faced RPMs.

2. Although abraded plastic-faced RPMs improve in SI when they are wet, they only do so if they are reasonably clean. Abraded RPMs improve much less under wet conditions if they are dirty.

3. Although heat/cold thermal cycling such as that encountered in many Districts on highways affects the retroreflectivity of both glass-faced and plastic only RPMs, glass-faced RPMs tend to improve by a significant margin, as much as 34% after being subjected to elevated temperatures, while plastic-faced RPMs decline somewhat under temperature stress. No explanation for this behavior was provided by RPM manufacturers, who have also noted this phenomenon. The thermal shock that each RPM is subjected to on being installed using 340 to 370 degree F bituminous mastic was not found to have significant detrimental effects on any of the RPMs that the Texas SDHPT is currently installing on Texas highways.

4. In both laboratory tests and in controlled access field tests in which all the different RPMs currently purchased by SDHPT were subjected to run-over by a test vehicle, glass-faced RPMs were far superior to plastic-faced RPMs. Whereas 10 passes of a weighted garnet cloth abrader would effectively eliminate the retroreflective performance of any plastic-faced RPM, as many as 100 passes on glass-faced RPMs produced very little degradation. These results were replicated with an actual vehicle in the run-over tests. The tests conducted indicate the most durable RPM now being purchased by SDHPT is the Model 948 Stimsonite RPM.

5. On plastic-faced RPMs subjected to abrasion, myriads of scratches in the outer surface scatter light rather than transmit it directly to the reflective cube-corner prism array immediately underneath. The greatly reduced light that does get to the reflective surfaces is scattered yet again as it leaves the retroreflector through the scratched outer surface. Glass-faced reflectors are far more abrasion-resistant. If the thin glass layer is shattered, then scatter is greater than with an abraded

plastic-faced RPM. Plastic-faced RPMs degrade rather quickly after they are installed to some low asymptotic level, and then unless they are broken, decline rather slowly thereafter. Glass-faced RPMs stay bright unless they are damaged in such a way that the glass face shatters all over the reflective surface but stays in place. Under those conditions, they "go out" abruptly. If the glass face cracks away, then the plastic face directly underneath acts just like an originally all-plastic RPM. A glass-faced RPM may have several broken or chipped areas on it and in day-light look much more damaged than a plastic-faced RPM installed near it, but may well perform much better as a retroreflective device.

Feasibility of RPM Restoration

1. Since clean but abraded plastic-faced RPMs can be temporarily restored to some of their original retroreflective performance by wetting the surface and thus filling in the scratches, a preliminary study was done to see if a clear coating of some kind would produce more lasting results. In such a way, degraded RPMs could be restored to some condition of use and replacement postponed under certain conditions. Restoration, using an acrylic and an epoxy coating, more than doubled the effective SI of a group of abraded plastic-faced RPMs. Tire abrasion tests and brief exposure to harsh December temperature extremes on the roof of a Texas A&M University building were encouraging.

Experience of Other States with Retroreflective RPMs

1. Three States with similar weather conditions to Texas were contacted: Florida, Georgia, and California. All reported adhesion problems which have much improved since adopting a bituminous mastic. Although some quality control problems have occurred in the past with glass-faced RPMs, all three states use them extensively if not exclusively because of their superior durability with regard to retroreflectivity.

RECOMMENDATIONS

1. The Infrared Field Measurement System developed by TTI under this project is in prototype form. A brief informational videotape on this system has been prepared and forms part of this final report. The system should be further developed into final production form and tested in at least one SDHPT district.

2. The tabled threshold information contained in Section 4 should be considered for use as a tool by the districts in deciding when to replace RPMs. Until such time as the on-road RPM measurement system is fully developed and made available, samples of RPMs suspected to be performing below an acceptable level would need to be removed from the roadway for laboratory measurement. Alternatively, a procedure could be developed in which reference RPMs with specific intensities matching the predetermined minimum

acceptable SI for particular applications are prepared. The reference RPM could then be temporarily installed adjacent to in-service RPMs which are suspected of being below acceptable SI values, thereby providing a point of reference for subjective visual comparisons. Preparation of the reference samples could be accomplished by obscuring a portion of the reflective surface of a new RPM with tape, as discussed in Section 4, pages 31 and 35. Both logistic and worker-safety concerns mitigate against routine use of such a procedure or its implementation for verifying the retroreflective performance of large numbers of individual RPMs. Rather, this approach should be considered in cases where a substantial number of RPMs appear, upon visual inspection, to be of questionable utility. Visual comparisons, using the appropriate reference RPM can then be made to verify or refute that replacement is advisable.

To simplify its use, the information tabled in Section 4 could be synthesized into a simple algorithm suitable for personal computers readily available in district offices.

3. Maintenance supervisors should be advised that just because part of an RPM face is cracked or broken, it does not necessarily mean the RPM is no longer usable. The threshold and durability studies indicated that even if more than half the surface is badly damaged, the specific intensity of the remaining portion may be sufficient to provide adequate reflectivity. This is especially true for glass-faced units.

4. Plastic-faced RPMs will work well in protected areas or for short-term installations, but otherwise will degrade rather rapidly to unacceptable levels of performance, as compared to glass-faced RPMs. For most applications, we recommend that SDHPT consider the use of glass-faced RPMs.

5. Further study of clear coatings suitable for application by maintenance crews in maintenance zones is warranted from the results obtained in this study, if SDHPT decides to continue to install large numbers of plastic-faced RPMs. Methods of application (which includes cleaning the RPMs) would also have to be developed. The cost/benefit of such an approach, and when it would be used, also needs to be studied.

6. The SDHPT has all the necessary equipment in its D-9 Laboratory to adopt the ASTM E 809-81 Standard Practice for Measuring Photometric Characteristics of Retroreflectors for measuring the retroreflectivity of raised pavement markers and other similar small devices. Tex-842-B should be updated to this procedure, or modified to reference this procedure. This will place Texas in conformance with a national standard.

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APPENDIX A

TTI Photometric Laboratory
Raised Pavement Marker Measurement Procedure

Basic Photometric Equipment

The Photometric Laboratory at the Riverside Campus of Texas A&M University is furnished with a Tektronix J16 Digital Photometer. The J16 Digital Photometer/Radiometer is a compact, battery- or AC-operated instrument primarily intended for calibrated measurements of the intensity of radiation over the 250 to 1200 nanometer (nm) wave-length range. This instrument is equipped with a 1 degree luminance probe, an 8 degree luminance probe, and both cosine-corrected and uncorrected illuminance probes. The illuminance and luminance probes each have a photodiode sensor with a filter to match its response to that of the C.I.E Photopic Curve. The AC power supply is used in the laboratory but the battery pack is available for portable operation. The bottom of all probes and the J16 case have a standard 1/4 - 20 mounting socket for use on optical benches or tripods. The range of measurement for the illuminance probes is 0.001 to 1,999 Foot Candles. The range of measurement for the luminance probes is 0.1 to 199,900 Foot Lamberts. The 8 degree luminance probe is usable from infinite focus to 18 inches from the front of the lens.

Test Procedure for Evaluating Raised Pavement Markers

The following procedure is used for determining the specific intensity of new retroreflective raised pavement markers. Slight modifications to this procedure are necessary to accommodate evaluation of dirty or wet RPMs.

1. The test specimens are selected from the stock of markers stored in the laboratory located at the Texas A & M University Riverside Campus. The markers are washed in warm water and mild detergent and allowed to air dry.

2. Immediately prior to testing, the faces of the RPMs are cleaned with commercial glass cleaner and a soft cloth.

3. The alignment of the measurement apparatus is checked and, if necessary, corrected prior to each session. The arrangement of the apparatus is such that the incident light beam strikes the RPM perpendicular to, and at the level of, the base of the reflecting face.

4. The Illuminance Probe (Tektronix Model J6501) of the Tektronix Photometer (Model J16) is located adjacent to, and approximately 11 inches in front of, the light source. It is positioned 3/4 inch above a line from the filament of the light source and the leading edge of the base of the test specimen. This arrangement allows an entrance angle of 0 degrees and an angle of 0.2 degrees from the RPM to the illuminance probe.

5. At this point, the lab is darkened and the J16 is calibrated.

A 180 degree Illuminance Probe (Tektronix Model J6511) is connected via the 25-foot attached cable to the main body and the probe is covered. In this condition, the calibration adjustment is manipulated such that the instrument reads zero on the lowest scale.

6. The light source is turned on. The light source is a Q-Beam Spotlight (Brinkman Model 800-1600-0) which has an intensity of approximately 300,000 Candles. The power supply for this source is a 12 Volt battery charger connected to line voltage. Illuminance at the front of the goniometer is measured by removing the cover of the J6511 probe and holding it in the position of the test specimen at the front of the goniometer. This value is recorded, in foot-candles, as Incident Illuminance (E_i). This measurement is repeated at the end of each test session and, if a large number of specimens are to be examined, approximately every 30 minutes.

7. The Illuminance Probe (Tektronix Model J6501), is now connected to the main body via an Interconnecting Cable (Tektronix Part No. 012-0414-02) and the illuminance of the empty goniometer is recorded, in foot-candles, as Ambient Illuminance (E_a). This measurement is also repeated at the end of each test session and, if a large number of specimens are to be examined, approximately every 30 minutes.

8. The goniometer has been modified to allow the placement of a moveable back plate to be placed in positions to ensure that all RPMs of each type are in exactly the same place in relation to the light source and measurement probe. The back plate is positioned for the RPM type under test and the clean, dry specimen is placed on the stage and the illuminance is measured and recorded, in foot-candles, as Probe Illuminance (E_p).

9. The values recorded, along with the dimension of the test apparatus, are used to calculate the specific intensity of the specimen RPM as follows:

$$SI = (E_r \times D^2) / E_i$$

where
SI = specific intensity
E_r = $E_p - E_a$ = Reflected Illuminance (foot-candl8es)
D = Distance (ft) from the RPM to Illuminance Probe (Model J6501)

Appendix B

Statistical Summary Tables

This Appendix contains summary tables for the analyses of variance conducted for several of the empirical studies reported in Section 5 of this report. Tables are provided for the following studies:

Tables B-1 and B-2.
Thermal Stress Study 1: The Effect of Thermal Stress on the Photometric Performance of Retroreflective Raised Pavement Markers

Table B-3
Thermal Stress Study 2: Thermal Shock from RPM Adhesive

Table B-4 and B-5
Abrasion Study 2: The Effect of Tire Impacts on RPM Photometric Performance

Table B-1. Heat stress ANOVA summary tables. (Section 5: Thermal Stress Study 1)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
TYPE	4	88 911 948 MINI
CYCLE	8	1 2 3 4 5 6 7 8
RPM	40	26A 26B 27A 27B 28A 28B 29A 29B 30A 30B 31A 31B 32A 32B 33A 33B 34A 34B 35A 35B 36A 36B 37A 37B 38A 38B 39A 39B 40A 40B 44A 44B 45A 45B 46A 46B 47A 47B 48A 48B

Number of observations in data set = 320

General Linear Models Procedure

Dependent Variable: % DELTA SI

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	67	177047.6415	2642.5021	164.13	0.0001
Error	252	4057.2323	16.1001		
Corrected Total	319	181104.8738			

R-Square	C.V.	Root MSE	%DELTA SI Mean
0.977597	84.96692	4.012496	4.72242188

General Linear Models Procedure

Dependent Variable: % DELTA SI

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TYPE	3	135218.7284	45072.9095	2799.54	0.0001
RPM(TYPE)	36	14124.1489	392.3375	24.37	0.0001
CYCLE	7	15177.4145	2168.2021	134.67	0.0001
TYPE*CYCLE	21	12527.3496	596.5405	37.05	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	135218.7284	45072.9095	2799.54	0.0001
RPM(TYPE)	36	14124.1489	392.3375	24.37	0.0001
CYCLE	7	15177.4145	2168.2021	134.67	0.0001
TYPE*CYCLE	21	12527.3496	596.5405	37.05	0.0001

General Linear Models Procedure

Dependent Variable: % DELTA SI

Tests of Hypotheses using the Type III MS for RPM(TYPE) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	135218.7284	45072.9095	114.88	0.0001

Table B-2. Cold stress ANOVA summary tables. (Section 5: Thermal Stress Study 1)

General Linear Models Procedure
Class Level Information

Class	Levels	Values
TYPE	4	88 911 948 MINI
CYCLE	3	1 2 3
RPM	39	50A 50B 51A 51B 52A 52B 53A 53B 54A 54B 55B 56A 56B 57A 57B 58A 58B 59A 59B 60A 60B 61A 61B 62A 62B 63A 63B 64A 64B 65A 65B 66A 66B 67A 67B 68A 68B 69A 69B

Number of observations in data set = 117

NOTE: Due to missing values, only 114 observations can be used in this analysis.

Dependent Variable: %DELTA SI

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	45	25927.55363	576.16786	7.48	0.0001
Error	68	5240.53856	77.06674		
Corrected Total	113	31168.09219			

R-Square	C.V.	Root MSE	%DELTA SI Mean
0.831862	172.7358	8.778767	5.08219298

Dependent Variable: %DELTA SI

Source	DF	Type I SS	Mean Square	F Value	Pr > F
TYPE	3	2069.01122	689.67041	8.95	0.0001
RPM(TYPE)	34	18994.08028	558.64942	7.25	0.0001
CYCLE	2	2158.15368	1079.07684	14.00	0.0001
TYPE*CYCLE	6	2706.30844	451.05141	5.85	0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	2069.01122	689.67041	8.95	0.0001
RPM(TYPE)	34	18994.08028	558.64942	7.25	0.0001
CYCLE	2	2211.02433	1105.51217	14.34	0.0001
TYPE*CYCLE	6	2706.30844	451.05141	5.85	0.0001

Dependent Variable: %DELTA SI

Tests of Hypotheses using the Type III MS for RPM(TYPE) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	2069.011225	689.670408	1.23	0.3123

Table B-3. Summary ANOVA tables.
(Section 5: Thermal Stress Study 2)

Class Level Information

Class	Levels	Values
TYPE	4	88 911 948 mini
PERIOD	2	post pre
ID	32	01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32

Number of observations in data set = 64

Dependent Variable: SI

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	35	19.76548131	0.56472804	310.76	0.0001
Error	28	0.05088363	0.00181727		
Corrected Total	63	19.81636494			

R-Square	C.V.	Root MSE	SI Mean
0.997432	2.740950	0.042629	1.55528125

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE [RPM type]	3	14.71922156	4.90640719	2699.87	0.0001
PERIOD [pre or post]	1	0.23985506	0.23985506	131.99	0.0001
TYPE*PERIOD	3	0.02381131	0.00793710	4.37	0.0121
ID(TYPE)	28	4.78259338	0.17080691	93.99	0.0001

Tests of Hypotheses using the Type III MS for ID(TYPE) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	3	14.71922156	4.90640719	28.72	0.0001

Tukey's Studentized Range (HSD) Test for variable: SI

NOTE: This test controls the type I experimentwise error rate, but generally has a higher type II error rate than REGWQ.

Alpha= 0.05 df= 28 MSE= 0.001817
Critical Value of Studentized Range= 3.861
Minimum Significant Difference= 0.0412

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	TYPE
A	2.1012	16	88
B	1.8455	16	911
C	1.4438	16	948
D	0.8306	16	mini

Table B-4. Summary ANOVA tables: Percent change.
(Section 5: Abrasion Study 2)

General Linear Models Procedure

Dependent Variable: %CHANGE

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	80	380974.4363	4762.1805	44.93	0.0001
Error	255	27029.9532	105.9998		
Corrected Total	335	408004.3895			

R-Square	C.V.	Root MSE	%CHANGE Mean
0.933751	41.16680	10.29562	-25.009524

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	4	56343.1913	14085.7978	132.89	0.0001
ID(TYPE)	51	40309.5783	790.3839	7.46	0.0001
IMPACTS	5	232365.9056	46473.1811	438.43	0.0001
TYPE*IMPACTS	20	46250.9769	2312.5488	21.82	0.0001

Tests of Hypotheses using the Type III MS for ID(TYPE) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	4	56343.19127	14085.79782	17.82	0.0001

Duncan's Multiple Range Test for variable: %CHANGE

Alpha= 0.05 df= 255 MSE= 105.9998

Number of Means	2	3	4	5
Critical Range	3.543	3.725	3.843	3.931

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	TYPE
A	-6.751	72	948
B	-13.238	60	911
C	-29.863	60	MINI
D	-33.447	72	28
E	-40.594	72	88

Duncan's Multiple Range Test for variable: %CHANGE

Alpha= 0.05 df= 255 MSE= 105.9998

Number of Means	2	3	4	5	6
Critical Range	3.865	4.064	4.193	4.289	4.370

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	IMPACTS
A	6.389	56	2400
B	-3.691	56	3800
B	-4.916	56	3600
C	-28.732	56	4000
D	-57.721	56	4200
D	-61.386	56	4400

Table B-5. Summary ANOVA tables: SI.
(Section 5: Abrasion Study 2)

General Linear Models Procedure

Dependent Variable: SI

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	85	339.1615941	3.9901364	47.38	0.0001
Error	306	25.7718424	0.0842217		
Corrected Total	391	364.9334365			

R-Square	C.V.	Root MSE	SI Mean
0.929379	17.13364	0.290210	1.69380102

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	4	78.3296424	19.5824106	232.51	0.0001
ID(TYPE)	51	59.6160226	1.1689416	13.88	0.0001
IMPACTS	6	139.1668197	23.1944699	275.40	0.0001
TYPE*IMPACTS	24	55.0855229	2.2952301	27.25	0.0001

Tests of Hypotheses using the Type III MS for ID(TYPE) as an error term

Source	DF	Type III SS	Mean Square	F Value	Pr > F
TYPE	4	78.32964243	19.58241061	16.75	0.0001

Duncan's Multiple Range Test for variable: SI

Alpha= 0.05 df= 306 MSE= 0.084222

Number of Means	2	3	4	5
Critical Range	0.092	0.097	0.100	0.103

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	TYPE
A	2.3714	70	911
B	1.9505	84	88
C	1.7975	84	28
D	1.2433	84	948
E	1.1243	70	MINI

Duncan's Multiple Range Test for variable: SI

Alpha= 0.05 df= 306 MSE= 0.084222

Number of Means	2	3	4	5	6	7
Critical Range	0.109	0.115	0.118	0.121	0.123	0.125

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	IMPACTS
A	2.3107	56	2400
A	2.2220	56	1200
B	2.1025	56	3800
B	2.0986	56	3600
C	1.5148	56	4000
D	0.8464	56	4200
D	0.7616	56	4400