TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-90/1151-1F		

4. Title and Subtitle	5. Report Date
Raised Pavement Marker Reflectivity	November 1990
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
V.J. Pezoldt, R.J. Koppa, R.A. Zimmer, A.T. Perry and H.W. Milsap	

9. Performing Organization Name and Address	10. Work Unit No.
Texas Transportation Institute The Texas A&M University System College Station, TX 77843-3135	11. Contract or Grant No. 2-10-88/9-1151
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address TX State Department of Highways & Public Transportation Transportation Planning Division P.O. Box 5051 Austin, TX 78763	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed for the State of Texas.

16. 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.

17. Key Words	18. Distribution Statement
Raised pavement markers, reflectivity, visual thresholds, photometry	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)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	117	

Form DOT F 1700.7 (8-69)

MOBILEYE EXHIBIT 1016

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

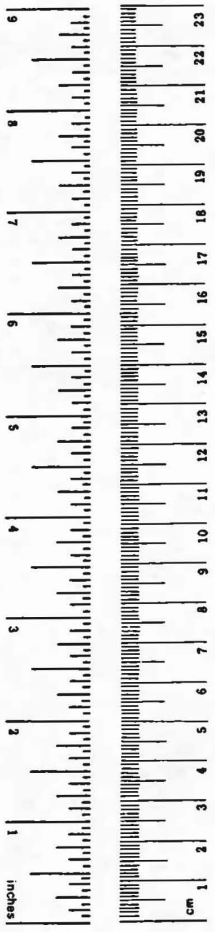
APPROXIMATE CONVERSIONS TO SI UNITS

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	centimetres squared	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

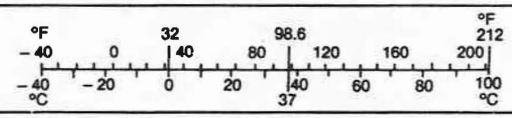


APPROXIMATE CONVERSIONS TO SI UNITS

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 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.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings and conclusions contained herein. This report does not necessarily reflect the views or official policies of the Texas State Department of Highways and Public Transportation whose support of this effort is gratefully acknowledged. This report does not constitute a standard, specification or regulation.

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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 retroreflective 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:

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

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

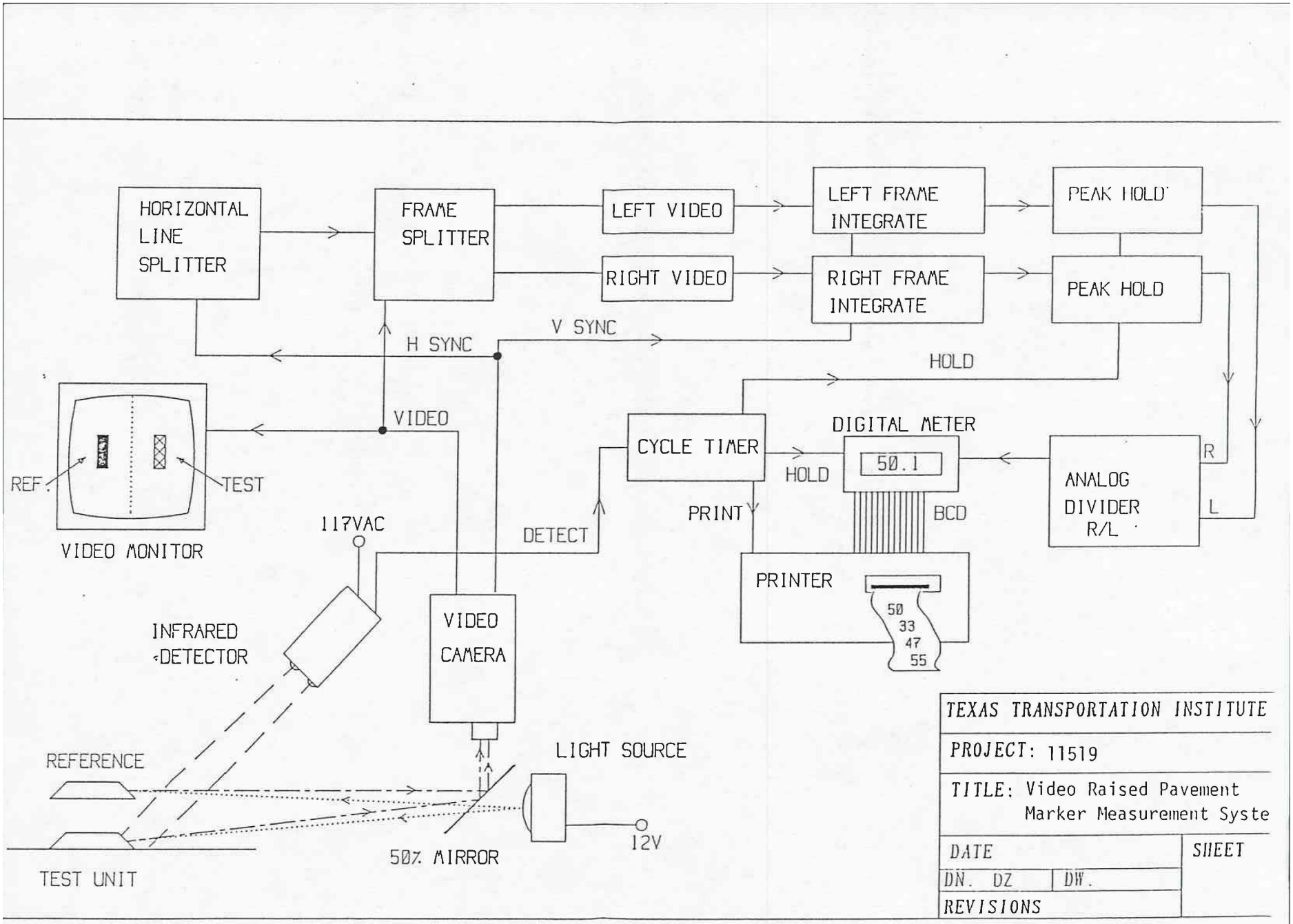


Figure 3-1. Video-based field measurement system

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

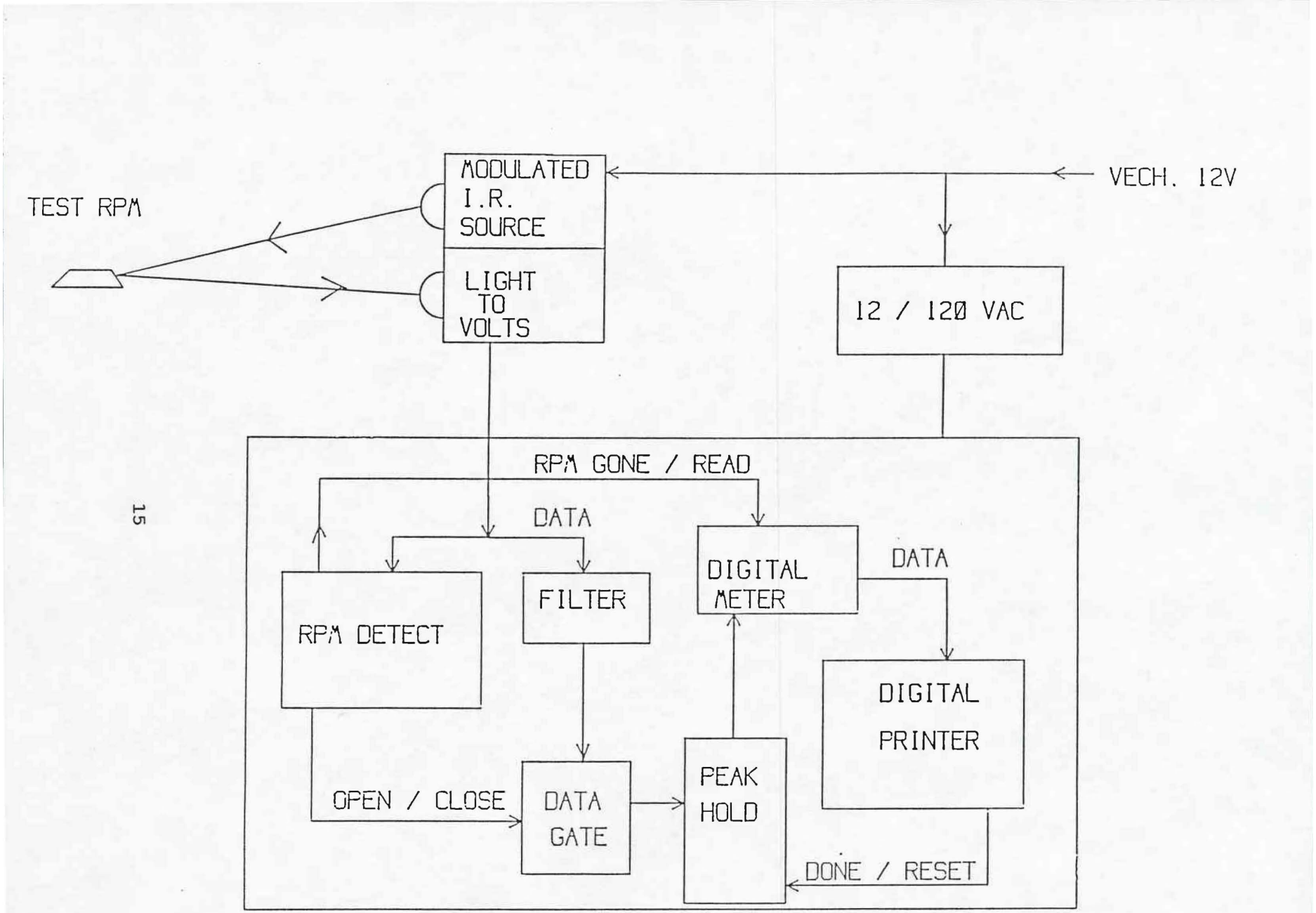


Figure 3-2. Block diagram of prototype infrared field measurement device

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

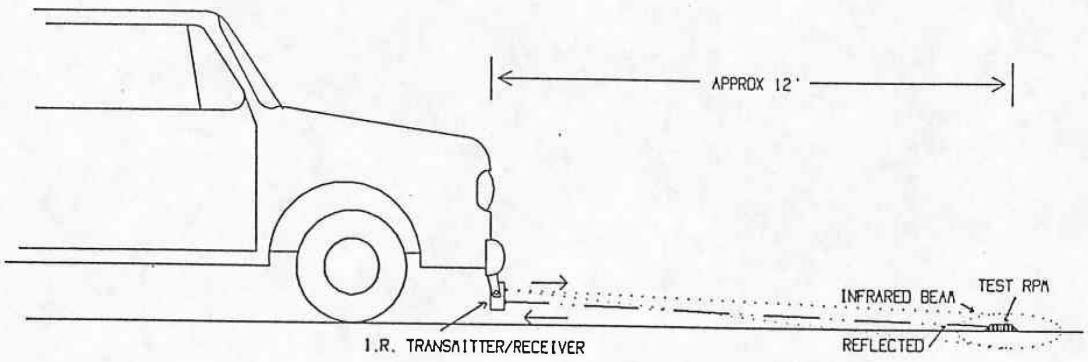


Figure 3-3. Configuration of installed infrared field measurement device.

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.

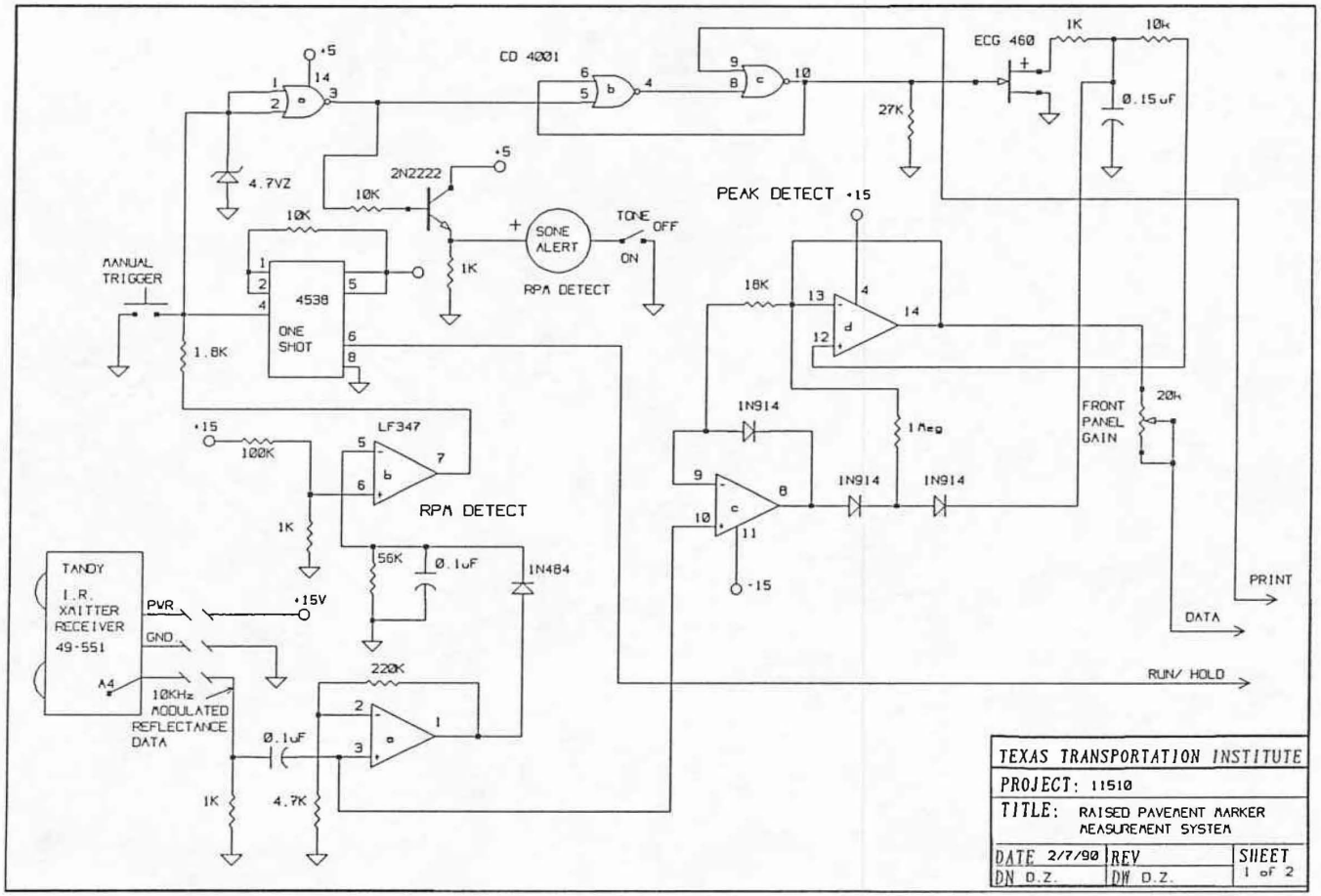


Figure 3-4. Schematic of infrared field measuring device (1).

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.

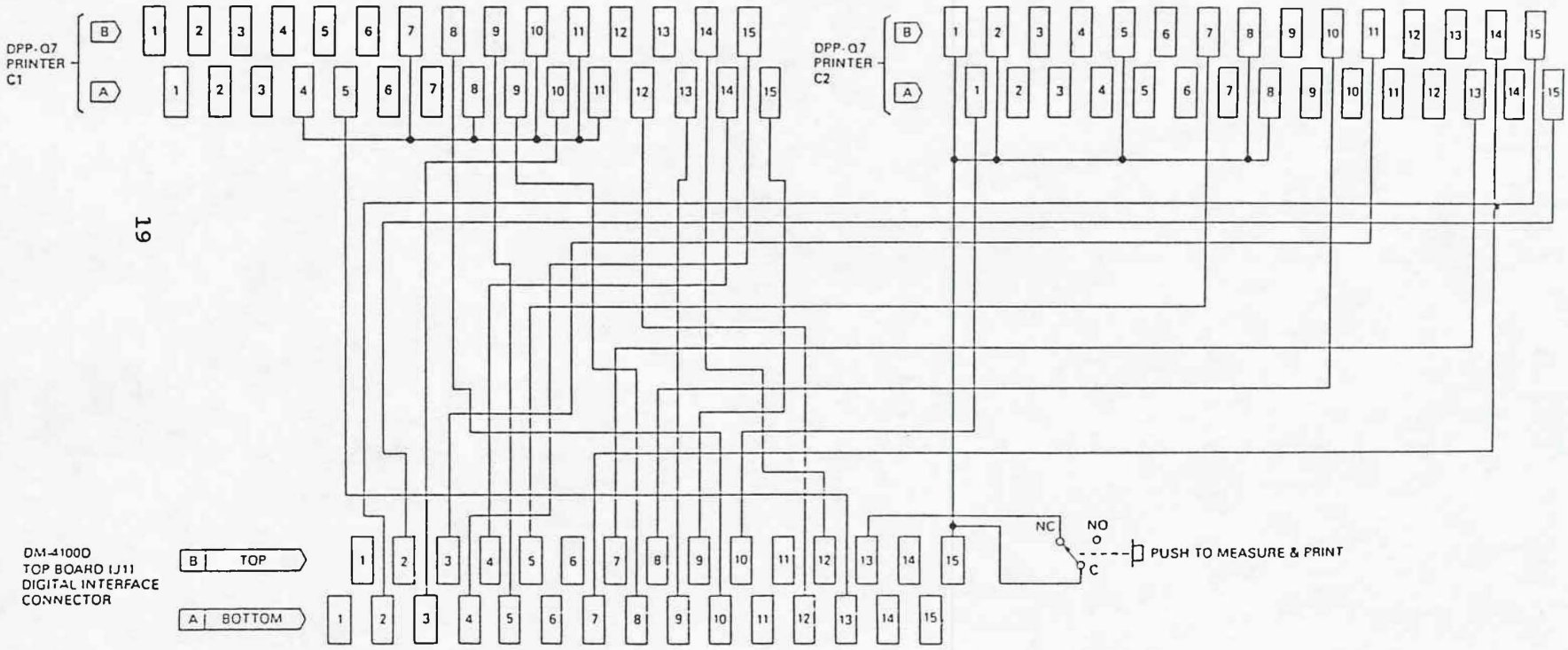


Figure 3-5. Schematic of infrared mobile field measurement device (2).

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-

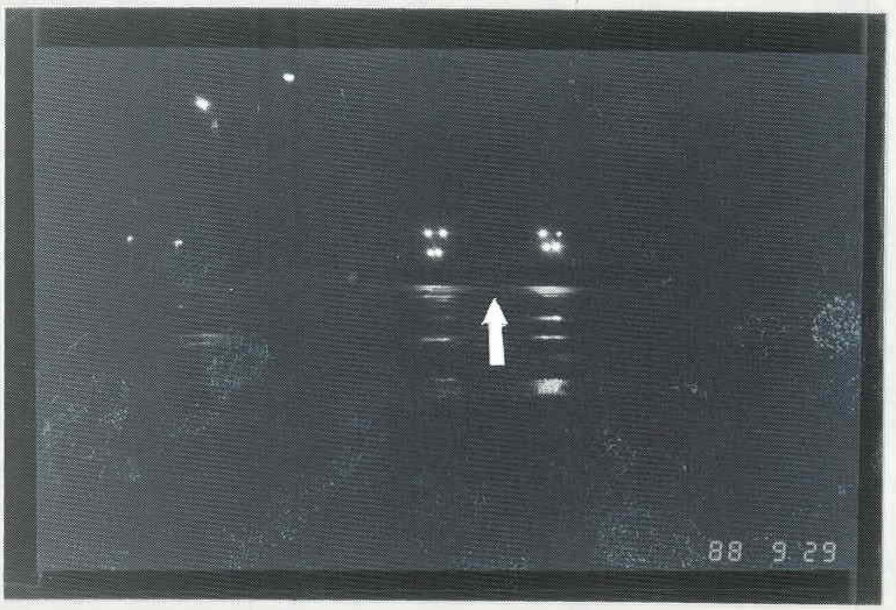


Figure 4-1. Urban environment visual scene.
(Arrow indicates faintly visible target RPM)

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	Viewing Condition: Rural % Detected	Viewing Condition: 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 0.00000001025 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 0.00000004869