UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

MOBILEYE GLOBAL, INC.,

Petitioner,

v.

MANDLI COMMUNICATIONS, INC.,

Patent Owner.

Case No. IPR2024-01110

Case No. IPR2024-01111

U.S. Patent No. 9,335,255

U.S. Patent No. 9,671,328

Declaration of Raymond Cruitt

I, Raymond Cruitt, state and declare as follows:

I. Introduction

1. I have prepared this Declaration in connection with petitions for Inter Partes Review of U.S. Patent No. 9,335,255 and U.S. Patent No. 9,671,328, which I understand will be filed concurrently with this Declaration.

2. I am currently a Research Analyst at Finnegan, Henderson, Farabow, Garrett & Dunner, LLP, 901 New York Avenue, NW, Washington, DC 20001-4413.

3. I am over eighteen years of age and am competent to make this Declaration. I make this Declaration based on my own personal knowledge and based on my knowledge of library science practices.

4. I earned a Master of Science in Library Science from the University of North Carolina at Greensboro in 2004, and a Bachelor of Arts in Philosophy from the University of North Carolina in 1998. I have worked as a librarian for eighteen years. I have been employed at Finnegan, Henderson, Farabow, Garrett & Dunner, LLP since 2019. Before that, from 2016 to 2019, I was employed in the Knowledge and Research Service Group (formerly, Information Research Service) at Northrop Grumman Corporation. And from

2005 to 2016, I was employed as a public and business librarian at Enoch Pratt Free Library, Baltimore, MD.

5. I am a member of the American Association of Law Libraries.

II. Standard Library Practice for Receiving, Cataloging, and Shelving Materials

6. I have knowledge of and experience with standard library practices regarding receipt, cataloging, and shelving of materials, including serial publications, available to the public. For example, I have knowledge of and experience with the Machine-Readable Cataloging ("MARC") system that libraries use to catalog materials.

7. Based on standard library practice, when a library receives an item, it stamps the item with the library name and often with a date that is within a day of receipt. The library will catalog the item within a matter of a one to two days of receiving it.

8. The MARC system was developed in the 1960s to standardize bibliographic records so they could be read by computers and shared among libraries. By the mid-1970s, MARC had become the international standard for bibliographic data, and it is still used today. Many libraries provide public access to their MARC records via the Internet and/or their electronic cataloging systems at the library.

9. The MARC record system uses specific three-digit numeric codes (i.e., field tags) from 001-999 to identify each field in a catalog record. For example, field tag **008** provides the six-digit date the item was cataloged (i.e., the date entered on file at the library). The first six characters of field tag **008** are in the "YYMMDD" format. Descriptions for all the character positions of field tag 008 are outlined here on the Library of Congress website. *See 008 - All Materials (NR)*, The Library of Congress, https://www.loc.gov/marc/bibliographic/bd008a.html (last visited July 5, 2024).

10. After an item is cataloged, the public may access the item by searching the catalog and requesting the item from the library. Standard library practice is to then shelve the item within a matter of a several days of cataloging it.

11. Given the matter of a several days between receiving an item, cataloging it, and shelving it, the total time between receiving an item and shelving it is a matter of a several days.

III. MARC Records

12. MARC uses a simple three-digit numeric code (from 001-999) to identify each field in the record. For example, field **245** identifies the title information of the work (which includes the title, other title information, and the statement of responsibility). Field **250** identities the edition of the work. Field **260**

identifies the publication information of the work. Field **264** identifies the Production, Publication, Distribution, Manufacture, and Copyright Notice information for the work. Field **020** identifies the International Standard Book Number (ISBN) for the work. And field **490** contains the series title.

IV. WorldCat, OCLC and Digital Libraries

13. WorldCat is the world's largest network of library content and services with 559,887,458 bibliographic records and ~3,446,566,579 holdings as of April 2024. (Source: https://www.oclc.org/en/worldcat/inside-worldcat.html). An Online Computer Library Center ("OCLC") number is a unique control number given to all bibliographic records in the WorldCat catalog. OCLC control numbers are often used by the public to search for specific records within WorldCat.

14. According to Digital Libraries by William Y. Arms, published by the MIT Press in January 2000 (and available here: https://www.cs.cornell.edu/wya/DigLib/text/titlepage.html), an informal definition of a digital library is "a managed collection of information, with associated services, where the information is stored in digital formats and accessible over a network. A key part of this definition is that the information is managed." Moreover, "Digital libraries contain diverse collections of information for use by many different users. Digital libraries range in size from

tiny to huge. They can use any type of computing equipment and any suitable software. The unifying theme is that information is organized on computers and available over a network, with procedures to select the material in the collections, to organize it, to make it available to users, and to archive it."

V. Ownership and Date-Stamp

15. Libraries have different policies on whether or not to date stamp publications. It is becoming increasingly common for libraries to no longer date stamp the publications they receive, particularly if they are in an electronic format. In the past, it was standard practice to affix an ownership stamp somewhere within the publication, usually on the cover page, verso of the cover page, or a designated page within the publication. The timing of when an ownership stamp is entered on the monograph or periodical can vary from one library to another. It could occur when the item is received in acquisitions after shipment to the library, or at the time of cataloging. Therefore, it is possible for there to be instances when the date of receipt precedes the cataloging date or vice versa.

VI. Serial Publications

16. A serial publication, often known as a "journal," is a resource that is issued in successive parts and has no predetermined conclusion. These successive parts are commonly referred to as "issues," and each issue is usually

chronologically numbered and dated. The presence of enumeration, years of coverage, and/or other chronological information also indicates a serial publication.

17. There are significant differences between cataloging finite resources (books/monographs) and continuing resources (serials). For serials, the catalog record provides information about the serial as a whole, including the first or earliest available issue. It also provides information as to holdings – the volumes and issues, with dates, received by the library and made available to the public. In serials cataloging, there are identifying characteristics unique to serials that are slightly different from monographs (books). The issue date for a print serial publication, for example, generally appears on the cover (front or back), the masthead page, the title page (if any), the table of contents page(s), or on the pages of the individual articles contained in the issue. More information regarding the unique aspects of cataloging serials can be found at this link: https://www.loc.gov/aba/pcc/conser/scctppt/Basic-2014/Basic-Trainee-Mannual.pdf

VII. Exhibits

18. This Declaration relates to the public availability, accessibility, and authenticity of the following article in **Appendix A**, *John J. Lumia "Mobile System for Measuring the Retroreflectance of Traffic Signs" Proceedings*

Volume 1385, Optics, Illumination, and Image Sensing for Machine Vision V: 8-9 November 1990, Boston, Massachusetts ("*Lumia*"). **Appendix A** is a true and accurate copy of Lumia. The frontmatter of Volume 1385 of Optics, Illumination, and Image Sensing for Machine Vision V published by SPIE—International Society for Optical Engineering, which contains the Lumia article is date stamped June 26, 1990. **Appendix A1** is a true and accurate copy of the MARC record for this item at the University of Wisconsin Verona library. The MARC record in **Appendix A1** for this item shows it was entered into the University of Wisconsin Verona library catalog on April 09, 1991, according to MARC line 008: 910409t19911991. Field tag 020 sets forth the unique ISBN for *Lumia* as "0819404527 (pbk)" which matches the ISBN on the title verso page. Field tag 245 denotes the title statement of the work along with the author as "a">Optics, illumination, and image sensing for machine vision / "c">Donald J. Svetkoff ... [and others]." Field tag 264 denotes place of publishing and year of publication "a" Bellingham, Wash, USA/ "c" 1991. Field tag 490 contains the series title: "Proceedings of SPIE – the International Society for Optical Engineering" SEE https://search.library.wisc.edu/catalog/999639084502121. Based on this evidence, my professional experience, and standard library practices, *Lumia*

would have been publicly available at University of Wisconsin - Verona within a few days of April 09, 1991, the date that it was catalogued.

19. This Declaration also relates to the public availability, accessibility, and authenticity of the following article in **Appendix B**, *Joseph T. Fitzpatrick "Unified Reflective Sign, Pavement And Delineation Treatments for Night Traffic Guidance" Highway Research Board Bulletin. 1960; 255: 138-145, which was* published by *Highway Research Board: Bulletin 255 (Night Visibilty: 1960)* ("*Fitzpatrick*") and was date stamped December 6, 1960. **Appendix B** is a true and accurate copy of *Fitzpatrick*. The MARC record in **Appendix B1** is a true and accurate copy of the MARC record for this item that was entered into University of Wisconsin Steenbock library catalog on August 05, 1980. The MARC record in **Appendix B1** reflects an updated catalog record with the item being registered in the catalog on August 05, 1980, according to MARC line 008: 800805s1960. SEE: https://search.library.wisc.edu/catalog/999748005302121. Based on this evidence, my professional experience, and standard library practices, *Fitzpatrick* would have been publicly available at University of Wisconsin - Steenbock within few days of December 6, 1960, the date that it was received.

20. This Declaration also relates to the public availability, accessibility, and authenticity of the following article in **Appendix C**, *Black,*

K.L. et al. NCHRP Report 346 (National Cooperative Highway Research Program) Report - 'Implementation Strategies for Sign Retroreflectivity Standards. Washington, D.C. (1992). Highway Research Board, 1964-2016: Washington, D.C. ("*Black*") and was date stamped June 1, 1992. **Appendix C** is a true and accurate copy of *Black*. The MARC record in **Appendix C1** is a true and accurate copy of the MARC record for this item at the University of Wisconsin Verona library and shows the catalog entry date as June 2, 1992, thereby demonstrating it was entered into the University of Wisconsin Verona library catalog on June 02. 1992, according to MARC line 008: 920602s1992. Field tag 020 sets for the unique ISBN for *Black* as "0309048699 (pbk.)" which matches the ISBN on the title verso page. Field tag 245 denotes the title statement of the work as "a">Implementation strategies for sign retroreflectivity standards / "c">K.L. Black." Field tag 490 contains the series title: "Report / National Cooperative Highway Research Program." SEE: https://search.library.wisc.edu/catalog/999685544002121. Based on this evidence, my professional experience, and standard library practices, *Black* would have been publicly available at University of Wisconsin – Verona within a few days of June 02, 1992.

21. This Declaration also relates to the public availability, accessibility, and authenticity of the following article in **Appendix D**, *Uding,*

Kenneth D. "Exact Road Geometry Output Program for Retroreflective Road Sign Performance" Highway Operations, Capacity, and Traffic Control. Transportation Research Record, Issue 1421. (1993) ("*Uding*") contained in the serial *Traffic Control Devices, Visibility, and Traffic Signal* Systems *(No. 1421) Traffic Research Record, 'Highway Operations Capacity, and Traffic Control' 1996* and date stamped January 09, 1996. **Appendix D** is a true and accurate copy of *Uding*. The MARC record in **Appendix D1** is a true and accurate copy of the MARC record at the Linda Hall Library for this item and shows the serial Transportation Research Record was entered into the current Linda Hall Library catalog on April 04, 1975, and includes volumes no. 1362(1992) – no. 1621(1998); this includes *No. 1421*. SEE: https://catalog.lindahall.org/discovery/sourceRecord?vid=01LINDAHALL_INST:LHL&docId=alma992991883405961&recordOwner=01LINDAHALL_INST. Based on the date stamp evidence, my professional experience, and standard library practices, *Uding* would have been publicly available at Linda Hall Library within a few days of January 09, 1996.

22. This Declaration relates to the public availability, accessibility, and authenticity of the following article in **Appendix E**, *McGee, Hugh W. et al. 'An Implementation Guide for Minimum Retroreflectivity Requirements for Traffic Signs' U.S. Dept. of Transportation, Federal Highway Administration,*

Research and Development, Turner-Fairbank Highway Research Center (1998) ("*McGee*"). **Appendix E** is a true and accurate copy of McGee. The MARC record in **Appendix E1** is a true and accurate copy of the MARC record at the University of Wisconsin, Madison library for this item and shows *McGee* was cataloged and available in at the University of Wisconsin, Madison library as early as November 2, 1998, according to MARC line 008: 981102s1998. Field tag 245 denotes the title statement of the work along with the author as "a">An implementation guide for minimum retroreflectivity requirements for traffic signs. SEE: https://search.library.wisc.edu/catalog/999896707502121. Based on this evidence, my professional experience, and standard library practices, *McGee* would have been publicly available at University of Wisconsin -Madison within a few days of November 2, 1998.

23. This Declaration relates to the public availability, accessibility, and authenticity of the following article in **Appendix F**, *Pezoldt, V.J. et al. 'Raised Pavement Marker Reflectivity' Research Report, 1151-1F. Texas Transportation Institute. TX State Department of Highways & Public Transportation Planning Division. 1990* ("*Pezoldt*"). **Appendix F** is a true and accurate copy of *Pezoldt*. **Appendix F1** is a true and accurate copy of the MARC record for this item at the Texas A&M Libraries and shows that *Pezold*

was cataloged and available in the library as early as August 9, 1991, according to MARC line 008: 910809d1990. Field tag 245 denotes the title statement of the work along with the author as “a">Raised pavement marker reflectivity / "c">V.J. Pezoldt [and others]. SEE: https://catalog.library.tamu.edu/Record/in00001038161#details. Based on this evidence, my professional experience, and standard library practices, *Pezoldt* would have been publicly available at Texas A&M Libraries within a few days of August 8, 1991.

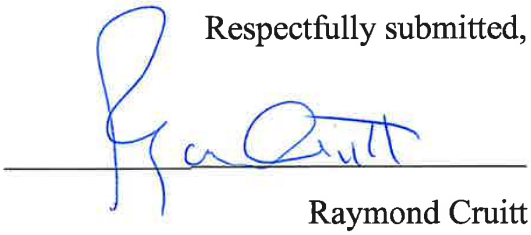
VIII. Conclusion

24. In signing this Declaration, I understand it will be filed as evidence in a contested case before the Patent Trial and Appeal Board of the United States Patent and Trademark Office. I understand I may be subject to cross-examination in this case and that cross-examination will take place within the United States. If cross-examination is required of me, I will appear for cross-examination within the United States during the time allotted for cross-examination.

25. I declare that all statements made herein of my knowledge are true, that all statements made on information and belief are believed to be true, and that these statements were made with the knowledge that willful false

statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Respectfully submitted,



Raymond Cruitt

Executed on August 1, 2024, in Washington, DC.

APPENDIX A

PROCEEDINGS

SPIE—The International Society for Optical Engineering

Optics, Illumination, and Image Sensing for Machine Vision V

Donald J. Svetkoff
Kevin G. Harding
Gordon T. Uber
Norman Wittels
Chairs/Editors

8–9 November 1990
Boston, Massachusetts

1990
UNIVERSITY LIBRARY



Volume 1385

CLASS SER.
SERIAL

PROCEEDINGS
SPIE—The International Society for Optical Engineering

Optics, Illumination, and Image Sensing for Machine Vision V

Donald J. Svetkoff
Kevin G. Harding
Gordon T. Uber
Norman Wittels
Chairs/Editors

8–9 November 1990
Boston, Massachusetts

Sponsored and Published by
SPIE—The International Society for Optical Engineering

KURT F. WENDT LIBRARY
COLLEGE OF ENGINEERING
UNIVERSITY OF WISCONSIN
MADISON, WI 53706



Volume 1385

SPIE (The Society of Photo-Optical Instrumentation Engineers) is a nonprofit society dedicated to the advancement of optical and optoelectronic applied science and technology.





The papers appearing in this book comprise the proceedings of the meeting mentioned on the cover and title page. They reflect the authors' opinions and are published as presented and without change, in the interests of timely dissemination. Their inclusion in this publication does not necessarily constitute endorsement by the editors or by SPIE.

Please use the following format to cite material from this book:
Author(s), "Title of Paper," *Optics, Illumination, and Image Sensing for Machine Vision V,* Donald J. Svetkoff, Editor, Proc. SPIE 1385, page numbers (1991).

Library of Congress Catalog Card No. 90-64018
ISBN 0-8194-0452-7

Published by
SPIE—The International Society for Optical Engineering
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone 206/676-3290 (Pacific Time) • Fax 206/647-1445

Copyright © 1991, The Society of Photo-Optical Instrumentation Engineers.

Copying of material in this book for internal or personal use, or the internal or personal use of specific clients, beyond the fair use provisions granted by the U.S. Copyright Law is authorized by SPIE subject to payment of copying fees. The Transactional Reporting Service base fee for this volume is $4.00 per article (or portion thereof), which should be paid directly to the Copyright Clearance Center (CCC), 27 Congress Street, Salem, MA 01970. Other copying for republication, resale, advertising or promotion, or any form of systematic or multiple reproduction of any material in this book is prohibited except with permission in writing from the publisher.

The CCC fee code for this volume is 0-8194-0452-7/91/$4.00

Individual readers of this book and nonprofit libraries acting for them are permitted to make fair use of the material in it, such as to copy an article for teaching or research, without payment of a fee. Republication or systematic or multiple reproduction of any material in this book (including abstracts) is prohibited except with the permission of SPIE and one of the authors.

Permission is granted to quote excerpts from articles in this book in other scientific or technical works with acknowledgment of the source, including the author's name, the title of the book, SPIE volume number, page number(s), and year. Reproduction of figures and tables is likewise permitted in other articles and books provided that the same acknowledgment of the source is printed with them, permission of one of the original authors is obtained, and notification is given to SPIE.

In the case of authors who are employees of the United States government, its contractors or grantees, SPIE recognizes the right of the United States government to retain a nonexclusive, royalty-free license to use the author's copyrighted article for United States government purposes.

Printed in the United States of America

ENGN
TA
1632
0685
1991

AMU82111

OPTICS, ILLUMINATION, AND IMAGE SENSING FOR MACHINE VISION V

Volume 1385

CONTENTS

Conference Committee v
Introduction vii

SESSION 1 ILLUMINATION AND SENSING METHODS AND SYSTEMS

1385-01 **Flexible object-centered illuminator**
G. T. Uber, Lockheed Missiles & Space Co., Inc.. 2

1385-03 **Positioning method using polarization-detecting optical sensor for precision robot systems**
M. Sakai, A. Nagayama, K. Sasakura, NTT Applied Electronics Labs. (Japan). 8

1385-04 **Mobile system for measuring retroreflectance of traffic signs**
J. J. Lumia, EKTRON Applied Imaging. 15

1385-05 **Laser Image Detection System (LIDS): laser-based imaging**
P. J. Hilton, R. Gabric, P. T. Walternberg, DSIR Industrial Development Christchurch (New Zealand). 27

1385-06 **Vision sensing and processing system for monitoring and control of welding and other high-luminosity processes**
J. E. Agapakis, Automatix, Inc.; J. O. Bolstad, Control Vision Inc.. 32

1385-29 **Recovery of aliased signals for high-resolution digital imaging**
S. John, Science and Technology Corp.. 39

SESSION 2 IMAGE AND INSTRUMENT MODELING AND ANALYSIS

1385-07 **Camera calibration using distance invariance principles**
G. V. Raju, P. Rudraraju, Ohio Univ.. 50

1385-08 **Semiautomatic calibration of the general camera model for stereovision**
E. Sung, H. Singh, D. H. Tan, Nanyang Technological Institute (Singapore). 57

1385-09 **Model for image sensing and digitization in machine vision**
M. Subbarao, A. Nikzad, SUNY/Stony Brook. 70

1385-10 **High-speed vision system based on computer graphics models**
C. Baur, S. Beer, Ecole Polytechnique Fédérale de Lausanne (Switzerland). 85

1385-11 **Robust image coding with a model of adaptive retinal processing**
R. Narayanswamy, Science and Technology Corp.; R. Alter-Gartenberg, Old Dominion Univ.; F. O. Huck, NASA/Langley Research Ctr.. 93

1385-12 **Experimental methodology for performance characterization of a line detection algorithm**
T. Kanungo, M. Y. Jaisimha, R. M. Haralick, J. Palmer, Univ. of Washington. 104

1385-14 **Noise statistics of ratiometric signal processing systems**
D. J. Svetkoff, T. G. Xydis, D. B. Kilgus, Synthetic Vision Systems, Inc.. 113

1385-13 **Excess carrier profile in a moving Gaussian spot illumination semiconductor panel and its use as a laser sensor**
M. H. Rahnavard, A. Bakhtazad, Shiraz Univ. (Iran). 123

(continued)

OPTICS, ILLUMINATION, AND IMAGE SENSING FOR MACHINE VISION V

Volume 1385

SESSION 3 OPTICAL PROCESSING AND DATA MANIPULATION

1385-15 **Using dynamic holography for iron fibers with submicron diameter and high velocity**
G. Xie, L. Hua, S. Patel, P. D. Scott, D. T. Shaw, SUNY/Buffalo. 132

1385-16 **Resolution enhancement in digital in-line holography**
L. Hua, G. Xie, D. T. Shaw, P. D. Scott, SUNY/Buffalo. 142

1385-17 **Morphological processing to reduce shading and illumination effects**
D. P. Casasent, R. H. Schaefer, J. O. Kokaj, Carnegie Mellon Univ.. 152

1385-27 **Optical Distributed Inference Network (ODIN)**
A. J. Bostel, P. W. McOwan, T. J. Hall, King's College London (United Kingdom). 165

1385-28 **Optical correlator vision system for a manufacturing robot assembly cell**
R. W. Brandstetter, N. J. Fonneland, R. Zanella, M. Yearwood, Grumman Aerospace Corp.. . . . 173

1385-30 **Spatial frequency filtering on the basis of the nonlinear optics phenomena**
A. D. Kudryavtseva, N. V. Tcherniega, G. L. Brekhovskikh, A. I. Sokolovskaya, P.N. Lebedev Physical Institute (USSR). 190

1385-18 **Hybrid pattern recognition system for the robotic vision**
Y. Li, M. Zhao, L. Zhao, Xian Institute of Optics and Precision Mechanics (China). 200

1385-19 **Reconstruction algorithm of displacement field by using holographic image**
K. Chen, Z. Xu, Z. Wen, Y. Chen, Southeast Univ. (China). 206

SESSION 4 THREE-DIMENSIONAL IMAGING TECHNIQUES AND SYSTEMS

1385-20 **Range data analysis using cross-stripe structured-light system**
W. Kim, Univ. of Texas/Dallas. 216

1385-21 **Color-encoded depth: an image enhancement tool**
L. H. Bieman, Industrial Technology Institute. 229

1385-22 **Defocused white light speckle method for object contouring**
A. K. Asundi, Univ. of Hong Kong (Hong Kong). 239

1385-23 **Single-lens moire contouring method**
K. G. Harding, E. Kaltenbacher, L. H. Bieman, Industrial Technology Institute. 246

1385-24 **Shape from shading with circular symmetry**
M. A. Gennert, Worcester Polytechnic Institute. 256

1385-25 **Robust stereo vision**
S. S. Sinha, S. Moezzi, B. G. Schunck, Univ. of Michigan. 259

1385-26 **Stereo matching by energy function minimization**
M. A. Gennert, B. Ren, Worcester Polytechnic Institute; A. L. Yuille, Harvard Univ.. 268

1385-31 **Monocular passive range sensing using defocus information**
K. V. Prasad, R. J. Mammone, Rutgers Univ.. 280

Addendum 292
Author Index 293

A mobile system for measuring retroreflectance of traffic signs

John J. Lumia

EKTRON Applied Imaging, Bedford, MA 01730

1. ABSTRACT

There is a serious need for a practical system to evaluate the nighttime visibility of existing traffic signs and provide data for making decisions on sign replacement. A mobile system has been developed which can measure the average retroreflectance of sign legend and background from a moving vehicle during daylight hours. This system uses a video camera to acquire sign images, a xenon flash as a source of light, a personal computer to analyze the sign images, and a laser rangefinder to measure the distance to the sign.

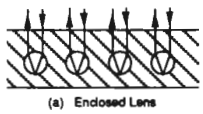
2. INTRODUCTION

The goal of the "Mobile System for Measuring Retroreflectance of Traffic Signs" (MSMRTS) is to permit the measurement of traffic sign retroreflectance during daylight hours, while traveling at speeds up to 55mph. Average values of both sign legend and background retroreflectance, in units of candelas per footcandle per square foot (commonly defined as R') are sought. The task is confounded by the fact that intensity of the retroreflected light from a sign depends on the angle between the source and detector, and this is generally not fixed for realistic dynamic situations. The design must be able to accommodate signs of different colors, shapes, sizes, and placement. The system should be simple and not pose a danger to the operator or other motorists.

The basic concept for the measurement of average legend and background retroreflection is the use of a video camera to record the sign, with an electronic flash source to provide a short burst of light sufficiently bright enough to overcome the sign luminance due to ambient daylight illumination. The video camera signal is then converted to a digitally sampled representation of the sign. Using the power of computer image processing, histograms of the retroreflected intensity distribution are exploited to yield average legend and background values. The use of a laser rangefinder in a moving system provides an accurate means of monitoring the distance from the vehicle to the sign and triggering image acquisition when a predetermined sign distance is reached.

3. BACKGROUND

A retroreflector is a device which turns light back toward its source, usually over a wide range of input angles. Signs are typically comprised of either retroreflective sheeting or retroreflective glass beads mounted directly on the face of the sign. The design of this system has been based largely on retroreflective sheeting. Three types of sheeting are commonly used for highway signs, consisting of enclosed glass beads, encapsulated glass beads, and cube-corner prismatic elements, as shown in Figure 1. The retroreflective properties of these materials are distinctly different from each other, as will be demonstrated later in Section 5.



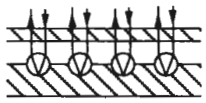




Figure 1.
Common retroreflective materials.

The goal of this system is to measure the Coefficient of Retroreflection, or R', in units of candelas per footcandle per square foot. This can be expressed as:[1]

$$R' = \frac{I}{E_n A} \quad (1)$$

where E_n is the normal illumination incident on the retroreflector, A is the area of the surface to be measured, and I is the reflected intensity. By suitable manipulation of these parameters, the retroreflectance can essentially be regarded as the absolute brightness of the retroreflective target for a given amount of incident illumination on the target. Arithmetically, this can be expressed as:

$$R' = \frac{L}{E_n} \quad (2)$$

where L is the luminance of the reflected light. Figure 2 shows the commonly accepted geometry and definitions as prescribed by the American Society for Testing and Materials[2] for evaluating retroreflective materials.

How are these quantities measured? The incident illumination is generally measured using an illuminance meter located at the target and facing the direction of light. A more realistic approach for a mobile system is to use the inverse-square law to infer the illumination from the source intensity, or $E = I/d^2$, where I is the intensity and d is the distance from the source to the detector (assuming that for the distances involved the source behaves as if it were a point). The intensity can be readily calibrated from laboratory measurements, while the distance can be measured using an appropriate laser ranging device. The reflected luminance may be measured with a luminance meter, which is similar to an illuminance meter except that the field of view (FOV) of the detector is limited to a sufficiently small angle. The use of a video camera effectively divides the FOV defined by the system magnification into smaller FOV's, thereby creating individual luminance meters at each sensing element site. In effect, the use of a video camera is a practical way for obtaining a large number of measurement samples from the sign so that representative legend and background retroreflectances may be calculated.

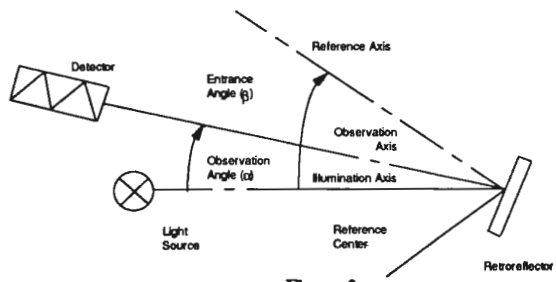


Figure 2.
Plan view of testing configuration showing observation and entrance angles.

The video system takes advantage of the contrast which typically exists between legend and background, anticipating a "bimodal" reflected intensity distribution. That is, the contrast difference allows the use of simple software algorithms to identify and group areas of similar intensity. For a typical two-color sign, these groups are expected to represent sign legend and background. The average value of each group corresponds to the average luminance, when properly calibrated. Assuming the illumination is known, the retroreflectance is readily obtained using Equation 2.

This approach is illustrated in the histogram plots of video imagery from an actual sign shown in Figure 3(a). This sign image was obtained with the MSMRTS at a distance of 200 feet under sunny outdoor conditions. Software is used to extract the sign area from the image to minimize the influence of pixel values corresponding to the area surrounding the sign. The result of this extraction is indicated by the box drawn in Figure 3(a). The histogram of the extracted sign area is shown in Figure 3(b), plotted as relative number of image points versus reflected light intensity (camera gray levels). First, histogram peaks are isolated, then

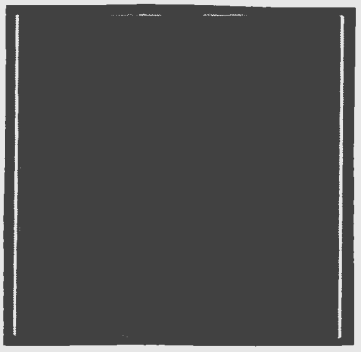


Figure 3(a). Image of typical sign with white legend on black background.

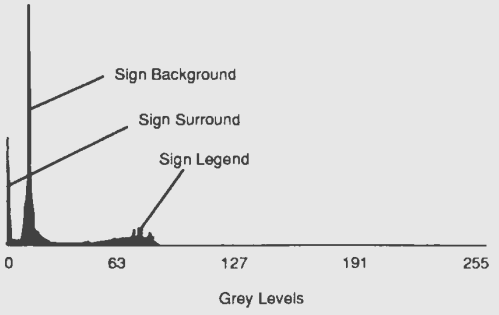


Figure 3(b). Related histogram of image of figure 3(a).

pixels within these peaks are summed to infer the relative area corresponding to each peak. Since signs typically have a larger background area than legend area, the histogram peak with the largest pixel count is considered to be the sign background as shown in Figure 3(b). The region to the right of the sign background peak has a smaller area and is identified as sign legend. The gray levels in these regions are then averaged to obtain sign legend and background retroreflectivities. The gray levels corresponding to image areas surrounding the sign are also indicated in Figure 3(b). The maximum value of sign surround generally does not exceed four gray levels, so excluding these from the histogram analysis is an effective way of obtaining accurate results without the need for sophisticated software to isolate signs having irregular shapes.

4. DESIGN, IMPLEMENTATION AND OPERATION

4.1. Design

The conceptual design for the mobile prototype is shown in Figure 4, with a block diagram of the system components shown in Figure 5. The design centers on the optical head, which mounts on top of the vehicle and which houses the cameras, electronic flash, and rangefinder. The operator is capable of manually aiming the optical head by means of a handle inside the van.

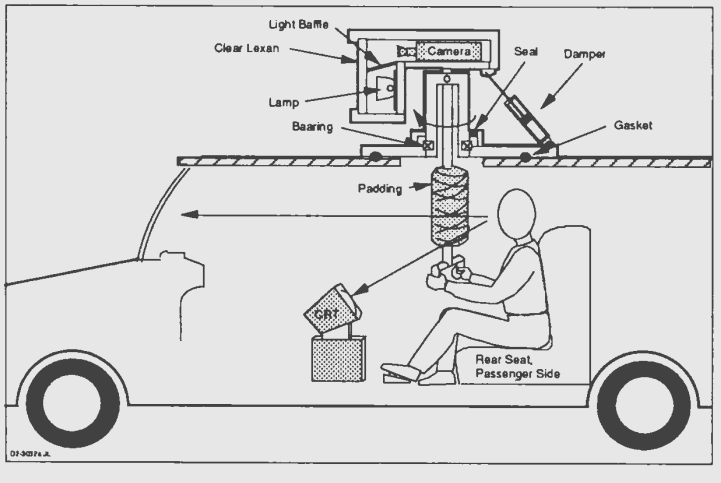


Figure 4. Conceptual design of MSMRTS mobile prototype.

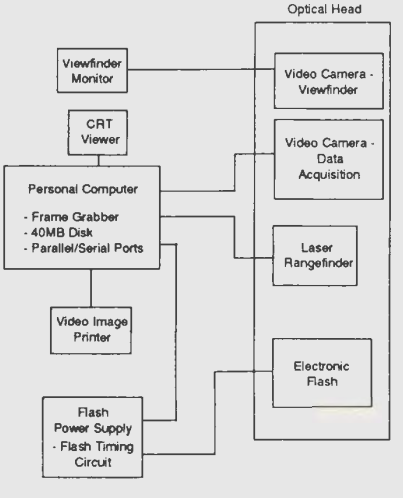


Figure 5. Block diagram of MSMRTS mobile prototype.

In order to satisfy the exposure requirements of this system, an electronically-shuttered video camera having a 1/1000 second duration is utilized. The camera uses a CCD area array measuring 8.8 x 6.6 millimeters (an aspect ratio of 1.33:1) with 491(H) x 384(V) pixels. The array has a signal-to-noise ratio of 46 db (200:1), with a sensitivity of 40 footcandles incident on a diffuse white target using a lens aperture of f/4.0 and a source color temperature of 3200°K (with infrared cutoff filter). The camera has a switchable automatic gain control (AGC) which is disabled since absolute video measurements are desired. The camera measures 5.5 x 2.5 x 3 inches (140 x 64 x 76 mm). A color conversion filter to correct the spectral distribution of the flash to 2856°K, and a filter to correct the camera response to a photopic behavior, are attached to the front of the lens.

Alignment of the optical head components is straightforward. The viewing camera, rangefinder, and flash have suitable adjusting mechanisms to permit alignment with respect to the data acquisition camera, which is fixed. Focus and lens aperture settings are preset and do not require adjustment.

4.2. Implementation

The design and implementation objectives of the mobile prototype were largely driven by physical and ergonomic considerations. The system should be easy to use and require little effort to operate. The system should be designed to permit access to all critical components for maintenance or service. The system should also be capable of withstanding typical environmental conditions such as weather, temperature, dust, and impact (stones, etc.).

The location of the optical head was a primary consideration in the design of the MSMRTS. Locating the head inside the vehicle may create unwanted light source reflections from the windshield and could be annoying to both driver and operator. Locating the head on the vehicle offers the possibility of having separate enclosures for both light source and cameras, thereby eliminating light source reflections off glass surfaces from reaching the camera.

External mounting exposes the system to wind forces which could make the system difficult to control while under way. The front surface area of the top cover and lower flash enclosure is equally distributed above and below the pivot center in an attempt to minimize torque due to frontal wind on the optical head. The entire optical head is balanced by a counterweight located at the rear of the baseplate and a suitably located pivot point. A spherical bearing is used to permit the optical head to swing in the front-to-back direction to control vertical aim and in the left-to-right direction to control camera angle. The bearing also permits the unit to be rotated for horizontal aiming. The unit can be aimed +/- 11 degrees vertically and rotated +/- 90 degrees. Cables are run through the center of the pivot arm to avoid exposure to the weather.

A 1990 Dodge B-150 Ram Van was purchased for testing of the mobile prototype concept (refer to Figure 6). The van comes with two individual seats in the front and a middle bench seat capable of seating three persons. In order to accommodate the optical head controls, the front passenger seat was relocated to the approximate location of the bench seat, and the bench seat was located further back towards the rear of the van.

A microcomputer with a video frame grabber is used to control the camera, flash, and rangefinder and to compute average sign retroreflectivity values. The computer has a 40 megabyte 3 1/2 inch hard disk drive for storing sign images prior to processing. The microcomputer is mounted close to the side of the van and next to the operator seat. A video printer is mounted next to the computer to provide hard copy output of the video images. The flash power supply, including a custom-designed flash trigger circuit board, is situated directly underneath the computer.

Three video monitors are secured to a table located directly in front of the operator, along with a computer keyboard attached to a slide out tray under the table (see Figure 7). The leftmost monitor is connected to the viewfinder camera and is used for aiming the optical head at the oncoming sign. The monitor in the center is connected to the video frame grabber and is used to view the sign image used for the data analysis. The rightmost screen is connected to the computer and serves as the system monitor.



Figure 6. Exterior photograph of MSMRTS.



Figure 7. Interior photograph of MSMRTS looking toward the front.

The power for the computer, flash, and monitors is derived from an inverter (made by Vanner, Inc.) which converts 12 volts DC supplied by the vehicle to 120 volts AC. The inverter is capable of supplying 1,000 watts continuously and is sufficient for supplying the needs of the system. The inverter is connected to two deep-cycle 12 volt batteries which act to store energy and effectively minimize the duty-cycle of the vehicle alternator. An isolator is used to prevent the vehicle battery from being discharged inadvertently. A voltmeter is located on the dashboard to monitor the state of the inverter batteries.

4.3. Operation

Figure 8 summarizes the operational scenario of the MSMRTS. The operator aims the optical head at an oncoming sign with the help of a video monitor attached to a wide angle video camera. The operator then presses a button located on the operator control handle to initiate rangefinder measurement software. The operator continues to "track" the sign in the video monitor, allowing the rangefinder to continuously measure the distance to the sign. When a predetermined sign distance (200 feet in "highway" mode, 100 feet in "local" mode) is reached, the computer triggers the electronic flash and the frame grabber acquires a video image from a second, narrow angle, video camera. The operator then may enter sign information (approximate milepost, route, and heading - or major street and cross-street) and the system stores this data together with the image and a file number for later identification. At the end of the run, the files are then analyzed to determine average legend and background retroreflectance for each sign and the results are printed on the screen. A video image printer is used for making hard copies of the resulting image for reports. Approximately 135 images may be stored before processing is required, although it is anticipated that minor software changes will increase the maximum capacity to 270 images.

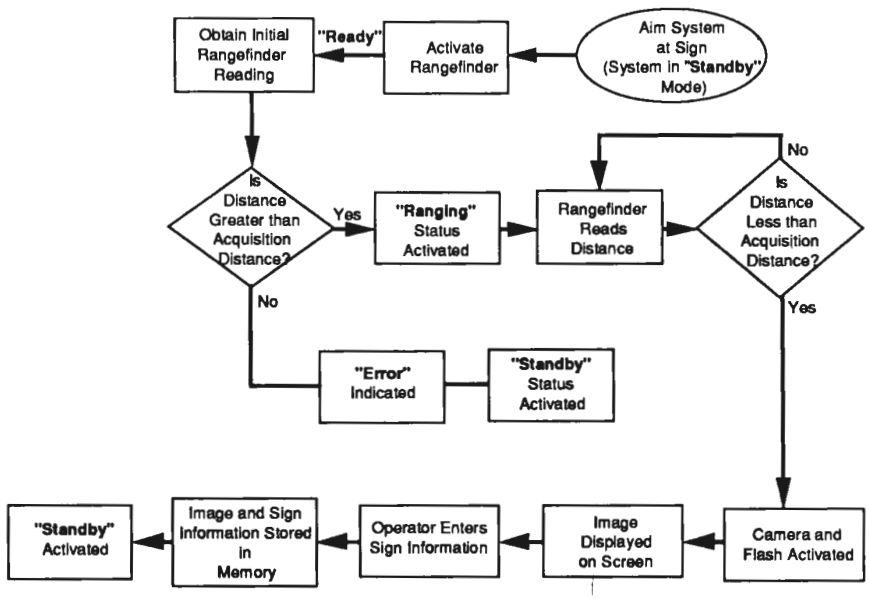


Figure 8. MSMRTS operational scenario.

5. FACTORS AFFECTING ACCURACY

5.1. Measurement geometry

In a system designed for in-situ measurements, the design of a system to achieve a specific measurement geometry is straightforward. In a moving system, the geometrical relationship between source, sign, and detector is constantly changing. Attention to this relationship is important since, in general, all retroreflective devices do not behave the same as the geometry is changed. The geometries of concern are observation angle and the entrance angle, as demonstrated previously in Figure 2.

Retroreflective materials are highly directional upon retroreflection, with prismatic sheeting most highly directional, followed by encapsulated and enclosed materials (refer to Figure 9). Assuming a fixed source-detector separation, the observation angle increases with decreasing distance to the sign. Realistically, the material of the sign being measured will most likely not be known, so that unless the angle is kept constant, or nearly so, for all situations, it will be nearly impossible to relate the measured value to a commonly measured observation angle (such as 0.2°). Hence, in order to maintain sufficient accuracy, there is a "distance window" in which the measurements need to be taken, assuming a fixed source-detector separation.

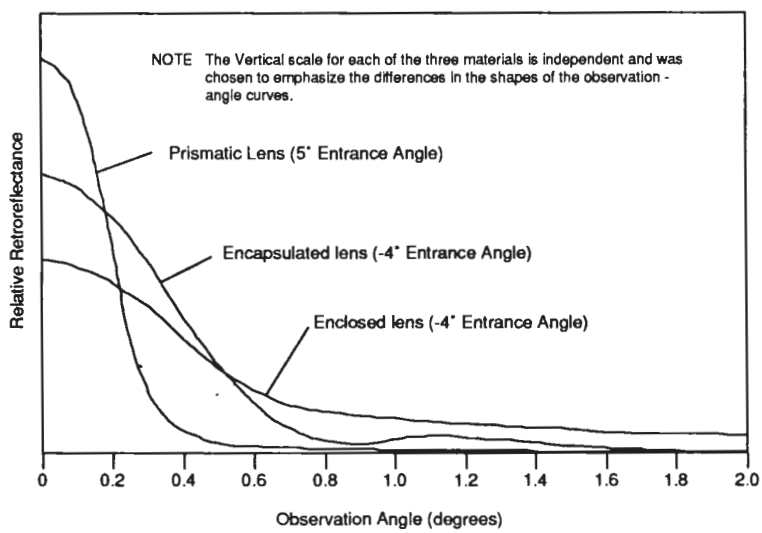


Figure 9. Relative retroreflectance versus observation angle.[4]

The effect of entrance angle (the angle between the axis of the light source and the normal to the sign) is far less severe. Generally, the reflected intensity falls by a worst case approximation of 1% per degree out to about 20 degrees for prismatic materials. In moving situations, it would be very difficult to measure the entrance angle. However, it can be expected that the entrance angle of most signs at appreciable distances is small, minimizing this effect. This angle is nearly the same for the measurement system as for the driver, so the impact of entrance angle on sign retroreflectivity is a realistic assessment of the sign's performance. Thus, compensation for entrance angle is not considered in the measurement system.

5.2. Ambient illumination effects

Since daylight measurements are required, it is necessary to either eliminate the effect of ambient illumination, or reduce the effect to a point to which it becomes tolerable with respect to the desired accuracy of the measuring system. Retroreflective effectiveness is usually relevant over small observation angles, and published measurements typically give data out to about 2°. However, retroreflective materials exhibit a small but appreciable coefficient of retroreflection at large observation angles (the angle subtended by the light source and the detector at the sign), as shown in Figure 9. For instance, the R' for enclosed-lens white materials is typically 100 - 120 at a 0.2° observation angle, but generally levels off to a value of approximately 0.3 at angles beyond 20 degrees. Ambient illumination levels can be quite high, approaching 10,000 footcandles for combined sun and clear sky, effectively offsetting the low R' value at large angles and creating appreciable daytime sign luminance levels.

In order to determine the effect of ambient illumination on sign luminance, samples of white enclosed, encapsulated, and prismatic materials were measured at various sun elevation angles. Measurements of sample luminance were taken with the plane of the material oriented vertically, but always in a direction facing closest to the sun. The experimental data shown in Figure 10 indicates that at any given angle, the enclosed-lens white material has the maximum luminance, followed by prismatic and encapsulated materials. At an angle of 20 degrees, the maximum ambient sign luminance was found to be 2,500 candelas per square foot for enclosed materials, 2,100 candelas per square foot for encapsulated materials, and 2,300 candelas per square foot for white prismatic materials. For solar angles less than 20 degrees, the rate of change of the ambient luminance increases more rapidly. This should be expected since the sun is creating a smaller observation angle with respect to the detector and thereby approaching the region of optimal retroreflective performance. This suggests that in order to minimize illumination requirements, it may be necessary to limit the measurement window to times when the sun is above an elevation of 20 degrees.

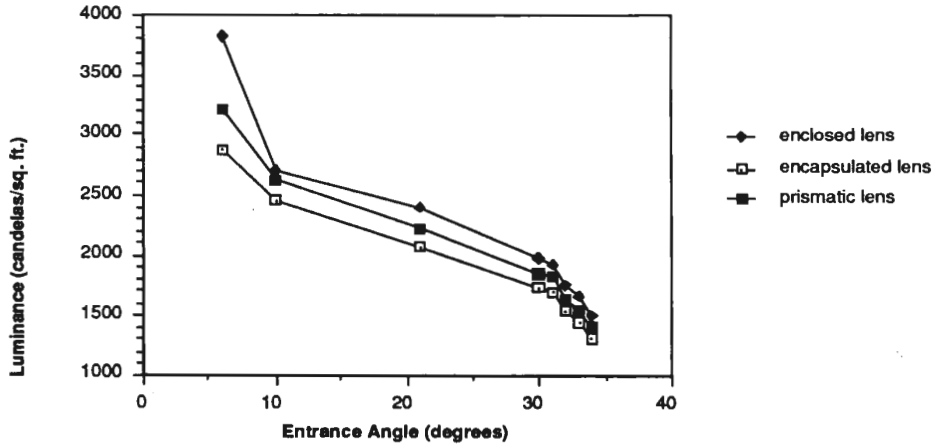


Figure 10. Sign luminance versus solar elevation for enclosed, encapsulated, and prismatic lens materials (white).

5.3. Intensity requirements

For a uniform retroreflective target possessing a given luminance due to ambient illumination, the light source must provide an adequate amount of additional exposure above the ambient signal so that the retroreflection due to the illumination system may be appropriately detected and isolated. This additional exposure factor can be denoted by a constant K. The value of K selected determines the capability of the system to reject the sign luminance due to ambient illumination. For example, a value of 20 implies a 20:1 ratio of artificial to ambient signal, and hence the measured data will have a 5 percent maximum error due to the presence of an ambient signal. The value of K could be as high as the signal-to-noise ratio of the camera, typically 200:1 for CCD cameras, but the additional demands required of the illumination system may not be realistic.

For electronic flash sources, the intensity is not constant over the duration of the flash. For this reason, it is customary to specify flash intensity in terms of an integrated value, denoted by It_f. It can be shown that this required "intensity exposure," to produce the necessary detection may be expressed as:[3]

$$It_f = \frac{K L_{amb} t_{cam} d^2}{R'} \qquad (\text{for } t_f < t_{cam}) \qquad (3)$$

where L_{amb} = maximum ambient sign luminance for a given material
t_{cam} = camera exposure time
t_f = flash lamp duration
d = distance to sign
R' = coefficient of retroreflection for a given material.

The units for It_f are in candela-seconds. It was found that in order to operate effectively with all materials, intensity requirements should be based on the retroreflective material (enclosed, encapsulated, or prismatic) which produces the worst case, or largest value of It_f. From Equation 3, it can be seen that It_f is greatest when L_{amb} is large and R' is small. From Figure 10, L_{amb} was chosen to be 2,500 candelas per square foot, based on the white enclosed-lens material. Furthermore, to obtain accuracy over a reasonable range of retroreflection, the value of R' was chosen to be the minimum recommended value corresponding to the enclosed white material, or 70 candelas per footcandle per square foot. Assuming a K value of 20 and a camera exposure time of 1 millisecond, the required value of flash exposure is 28,500 candela-seconds, as long as the flash duration is less than the camera exposure time. From Equation 3, flash exposure is directly proportional to K, indicating that system accuracy will be sacrificed if the required quantity of light is not available.

5.4. Electronic flash

The advantage of using an electronic flash is that large quantities of light are produced over short periods of time. For maximum efficiency, the flash duration should be less than or equal to the exposure time of the camera.

As Equation 3 indicates, exposure requirements are minimized when t_{cam} is short. It would, therefore, seem desirable to reduce t_{cam} as much as possible. However, as t_{cam} is reduced, the flash exposure time, t_{flash}, must be reduced as well. In general, there is an optimum flash duration in which light output efficiency is maximized for a given flashtube design. Also, the necessity for an appreciable quantity of light for this application generally requires a relatively long flash duration (on the order of 0.1 to 1 millisecond), but in moving situations, the duration needs to be short enough to "freeze" the effects of image motion due to vibration.

The electronic flash used in the MSMRTS has a duration of approximately 1 millisecond and produces 40,000 candela-seconds, nearly 40% greater than the 28,500 value described above. The spectral quality of electronic flash units are generally found to be in the daylight region of the spectrum, with typical color temperatures ranging from 5,000°K to 7,500°K, depending primarily on fill gas, pressure, and energy loading. The output is nominally continuous with few spikes which may adversely affect color measurement accuracy. The unit uses a long linear flashtube in a trough-type reflector having a parabolic cross-section, yielding a long, but narrow beam profile. In the more critical vertical direction, the total beam spread, defined at the 90% points, was measured to be approximately 2°.

5.5. Rangefinder accuracy

A commercially-available laser rangefinder is used to obtain sign distance information. This device uses a time-of-flight (TOF) method in which short pulses of laser light supplied by a laser diode are sent out to the target. By measuring the time to receive the returned pulse, and knowing the speed of light, the total round-trip distance can be calculated. This value is divided by two to obtain the actual distance to the target. The rangefinder operates at a sampling rate of 2,000 samples per second, but in order to improve measurement accuracy, the unit can average a number of samples to obtain the distance reading. The number of samples per reading is called the repetition rate. The 9,600 baud data rate of the serial interface limits the effective data transfer to approximately 133 readings per second, or 15 samples per reading, with a net estimated accuracy of $\pm$ 0.27 feet ($\pm$ 82 mm) under stationary conditions. At a constant speed of 40 mph (59 feet per second), the resulting distance resolution is estimated to be 0.30 foot. Experiments indicate that the accuracy of sign measurements taken at 40 mph is within 2% of measurements obtained while stationary. Measurement variability at 40 mph is found to increase by less than 1% over stationary measurements.

5.6. Image processing

The MSMRTS measures a fixed size region which is generally centered within the sign. Due to the differences in sign size, the image processing may have difficulty distinguishing between the dark background or legend and the image area surrounding the sign. This typically results in the determination of an incorrect threshold for the sign, producing an erroneous partitioning of legend and background regions. If this occurs, the result is easily observed since the video monitor displays an incorrectly thresholded image. The software has a feature permitting the operator to manually select the desired sign region or manually change threshold settings.

6. EXPERIMENTAL RESULTS

Ten signs were measured with the mobile system and compared to data obtained with a calibrated hand-held retroreflectometer. The signs used for this experiment had a white background color with background R' values ranging from approximately 4 to 350. Calibration of the system was accomplished by acquiring an image of a calibrated white sheeting material and computing a scale factor to convert the 8-bit digital gray levels of the calibration target image to R' values. Sixteen image samples were obtained for each sign using an observation angle of 0.2° and at a distance of 200 feet ("highway" mode). The same signs were measured by an Advanced Retro Technology 910F hand-held retroreflectometer (HHRR) calibrated with the same calibration target used to calibrate the MSMRTS. Six randomly distributed HHRR measurements of the sign background were made for each sign.

Figure 11(a) summarizes the comparative results of the MSMRTS and HHRR. Figure 11(b) shows the differences as a percent of the full scale (% FS) MSMRTS reading, where full scale was found to be 378 R'. From the graphs, it is evident that the results are in close agreement with measurements made with the HHRR. The MSMRTS measurements were found to be typically within

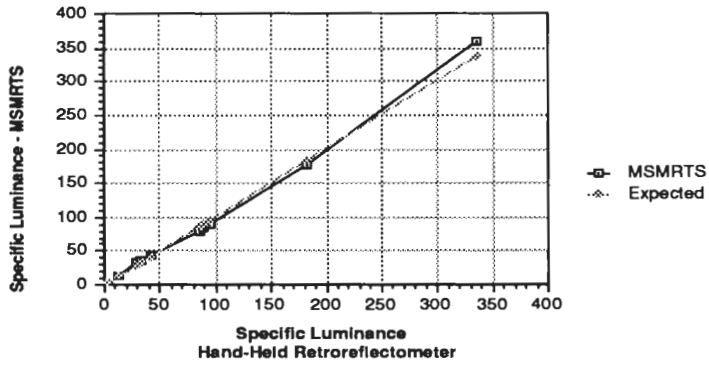


Figure 11(a). MSMTRS (maximum 378 R') versus hand-held retroreflectometer measurements.

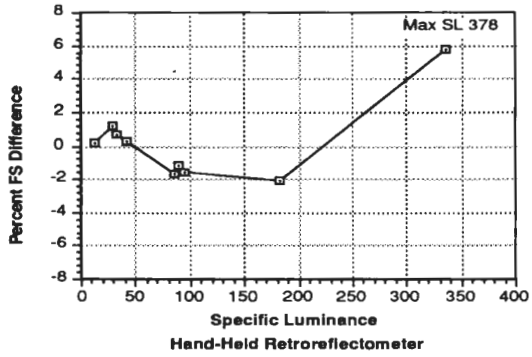


Figure 11(b). Percent difference of MSMRTS (maximum 378 R') compared to hand-held retroreflectometer.

3% FS of the HHRR measurements. It should be noted that differences between the MSMRTS and the HHRR are expected, since it may be difficult to obtain a representative average measurement for a sign which has sufficiently nonuniform retroreflectivity.

The data for the experimental results reported above were obtained with the vehicle in a stationary position. Vehicle speed is expected to have a minimal impact on sign measurement accuracy, as discussed previously in Section 5.5.

7. CONCLUSIONS

The research and analysis presented in this report indicate that a reasonably accurate mobile system for measuring the average retroreflectance of traffic signs during daylight hours is feasible. The conceptual design of the system is well suited for making measurements from a moving vehicle. The suggested components for this application are commercially available, minimizing the need for an extensive engineering effort to develop a production model MSMRTS.

8. ACKNOWLEDGMENTS

This work is being sponsored by the National Cooperative Highway Research Program (NCHRP) which is administered by the Transportation Research Board of the National Research Council, Contract No. HR 5-10.

9. REFERENCES

1. Standard Practice for Describing Retroreflection, American Society for Testing and Materials, ASTM Designation: E808–81, Philadelphia, 1981.

2. Federal Test Method Standard 370, Instrumental Photometric Measurements of Retroreflective Materials and Devices, General Services Administration, Washington, DC, 1977.

3. A detailed derivation is available from the author.

4. N. L. Johnson, "Accuracy in the Photometry of Retroreflectors," Proc. Soc. Photo-Opt. Instrum. Eng., Vol. 196, pp. 136-146, 1979.

APPENDIX B

HIGHWAY RESEARCH BOARD

Bulletin 255

RECEIVED
DEC 9 1960
UNIV. WIS. LIBRARY

Night Visibility: 1960

National Academy of Sciences—
National Research Council

publication 764

HIGHWAY RESEARCH BOARD

Officers and Members of the Executive Committee

1960

OFFICERS

PYKE JOHNSON, *Chairman* — W. A. BUGGE, *First Vice Chairman*

R. R. BARTELSMEYER, *Second Vice Chairman*

FRED BURGGRAF, *Director* — ELMER M. WARD, *Assistant Director*

Executive Committee

BERTRAM D. TALLAMY, *Federal Highway Administrator, Bureau of Public Roads* (ex officio)

A. E. JOHNSON, *Executive Secretary, American Association of State Highway Officials* (ex officio)

LOUIS JORDAN, *Executive Secretary, Division of Engineering and Industrial Research, National Research Council* (ex officio)

C. H. SCHOLER, *Applied Mechanics Department, Kansas State College* (ex officio, Past Chairman 1958)

HARMER E. DAVIS, *Director, Institute of Transportation and Traffic Engineering, University of California* (ex officio, Past Chairman 1959)

R. R. BARTELSMEYER, *Chief Highway Engineer, Illinois Division of Highways*

J. E. BUCHANAN, *President, The Asphalt Institute*

W. A. BUGGE, *Director of Highways, Washington State Highway Commission*

MASON A. BUTCHER, *Director of Public Works, Montgomery County, Md.*

A. B. CORNTHWAITE, *Testing Engineer, Virginia Department of Highways*

C. D. CURTISS, *Special Assistant to the Executive Vice President, American Road Builders' Association*

DUKE W. DUNBAR, *Attorney General of Colorado*

FRANCIS V. DU PONT, *Consulting Engineer, Cambridge, Md.*

H. S. FAIRBANK, *Consultant, Baltimore, Md.*

PYKE JOHNSON, *Consultant, Automotive Safety Foundation*

G. DONALD KENNEDY, *President, Portland Cement Association*

BURTON W. MARSH, *Director, Traffic Engineering and Safety Department, American Automobile Association*

GLENN C. RICHARDS, *Commissioner, Detroit Department of Public Works*

WILBUR S. SMITH, *Wilbur Smith and Associates, New Haven, Conn.*

REX M. WHITTON, *Chief Engineer, Missouri State Highway Department*

K. B. WOODS, *Head, School of Civil Engineering, and Director, Joint Highway Research Project, Purdue University*

Editorial Staff

FRED BURGGRAF — ELMER M. WARD — HERBERT P. ORLAND

2101 Constitution Avenue — Washington 25, D. C.

The opinions and conclusions expressed in this publication are those of the authors and not necessarily those of the Highway Research Board.

Contents

TRAFFIC OPERATIONS AS RELATED TO HIGHWAY ILLUMINATION AND DELINEATION

A. Taragin and Burton M. Rudy 1

Appendix 22

INFLUENCE OF TINTED WINDSHIELD GLASS ON FIVE VISUAL FUNCTIONS

Ernst Wolf, Ross A. McFarland and Michael Zigler 30

DARK ADAPTATION AS A FUNCTION OF AGE AND TINTED WINDSHIELD GLASS

Ross A. McFarland, Richard G. Domey, A. Bertrand Warren and David C. Ward 47

THE ASSOCIATION BETWEEN RETINAL SENSITIVITY AND THE GLARE PROBLEM

Robert H. Peckham and William M. Hart 57

SOME FACTORS AFFECTING DRIVER EFFICIENCY AT NIGHT

T.W. Forbes 61

AN EXPERIMENTAL LOW-COST LIGHTING SYSTEM FOR IMPORTANT HIGHWAYS IN RURAL AREAS

A.W. Christie 72

Appendix A 77
Appendix B 77
Appendix C 77

EFFECTIVENESS OF HOLLAND TUNNEL TRANSITIONAL LIGHTING DURING THE WINTER MONTHS

Alan T. Gonseth 79

SOME RESULTS OF COOPERATIVE VEHICLE LIGHTING RESEARCH

Thomas R. Kilgour 92

VISUAL COMFORT EVALUATIONS OF ROADWAY LIGHTING

Charles H. Rex and J.S. Franklin 101

ILLUMINATION REQUIREMENTS FOR ROADWAY VISUAL TASKS

H. Richard Blackwell, B.S. Pritchard and Richard N. Schwab. 117

DRIVER PERFORMANCE RELATED TO INTERCHANGE MARKING AND NIGHTTIME VISIBILITY CONDITIONS

J.E.P. Darrell and Marvin D. Dunnette 128

UNIFIED REFLECTIVE SIGN, PAVEMENT AND DELINEATION TREATMENTS FOR NIGHT TRAFFIC GUIDANCE

Joseph T. Fitzpatrick 138

VISUAL CHARACTERISTICS OF FLASHING ROADWAY HAZARD WARNING DEVICES

Jerry Howard and Dan M. Finch 146

ADVANCEMENT IN ROADWAY LIGHTING

Charles H. Rex 158

Appendix A 184
Appendix B 185
Appendix C 186

VISION AT LEVELS OF NIGHT ROAD ILLUMINATION V. LITERATURE 1959

Oscar W. Richards 190

Unified Reflective Sign, Pavement And Delineation Treatments for Night Traffic Guidance

JOSEPH T. FITZPATRICK, Manager, Technical Service, Reflective Products Division, Minnesota Mining & Manufacturing Company, St. Paul

Consideration of the perception factor in night visibility has led to the joint evaluation of a recognized guidance concept and new reflective materials recently installed at a typical interchange. The retro-reflective treatment was specifically designed to distinguish by color, brightness, and position the location and design of exit and merging ramps.

High intensity delineation was used for distant identification. For close approach, paved ramp surfaces were reflectorized for 200-300 ft. Yellow delineation and road surfaces for merging zones formed an integrated system denoting the required caution. For maximum contrast with its complement, and based on airfield practice for off-ramp guidance, a similar system in blue was used for exit areas and pertinent destination signs. Silver through lane delineation was retained with standard green guide signs.

To provide adequate differential between green and blue signs, a distinctive blue sheeting was employed. Color and brightness requirements also established criteria for delineation and reflective road treatments. With upper beams, the reflective blue roadway initially provides 6 foot-lamberts luminance at 200 ft, the yellow, 40 ft-l compared to the untreated pavement returning 0.08 ft-l.

The substantial increase in road surface luminance offers markedly improved contrast over the surround in both color and brightness. Integrated, color-keyed reflective systems thus afforded, suggest a method for effectively providing the motorist's visual cue and guidance needs night and day.

● CONSIDERABLE PROGRESS has been realized in those fields of night visibility related to the visual function and to effective design and use of vehicle lighting, roadway illumination and reflectorization. Substantial improvements in roadway visibility have resulted, in many cases with corresponding and demonstrable improvement in night driving characteristics and safety. However, the ultimate objective of increased perception and safety proportional to the visibility improvement encourages continued research, both for further improvement of visibility aids and their effectiveness.

The 1957 Symposium sponsored by the Armed Forces-NRC Committee on Vision directed attention to many of the pertinent visual problems. Among these was the suggestion that a substantial difference exists between what the driver should see and what he does see. Seeing while driving was defined by Brody as "selective directional seeing in a multivisual environment." Others suggested improvement in presentation of essential information to the motorist. Additional visual problems ascribed to night driving conditions included limited perceptual performance at mesopic levels of luminance, and visual disability or discomfort.

As an aid to selective and effective seeing, reflective materials have long been used on signs, delineators and road markings. Research in this field has increasingly concentrated on brightness, design and application possibilities. The consideration of additional color and shape coding in signs and markings — recommended by the Armed Forces-NRC Committee — has encouraged more research as have a number of related

military and industrial applications. As a result, recent technological developments have led to more versatile reflective materials including pavement markings exhibiting notably increased brightness and color utility, a correlate inasmuch as adequate color discrimination at mesopic levels and highway viewing distances requires either substantial luminance or areas.

To test these materials under typical field conditions, a cloverleaf interchange at the intersection of US 61 and Minnesota 36 was selected with the assistance and cooperation of the Minnesota Highway Department for an experimental installation and study. The complexity of the driving task at such locations has been reported by Forbes and Katz together with the need for increased warning distance, visibility, attention value and, particularly, choice limitation. Simple 2-choice channels afford least difficulty, provided sufficient conspicuity to insure early perception particularly after nightfall.

Accordingly, the reflective treatment at the test interchange was designed to clearly distinguish significant features of interchange design; namely, signs and markings, destination, precise location and design of ramps, speed change and through lanes. In view of the common purpose of related signs, speed change lanes and ramps, and to exclude possible confusion from invariable use of similar colored delineation and marking systems, the significant characteristics were further distinguished by color.

Consistent with the established use of yellow to denote caution, yellow reflective materials were employed at on-ramp and merging zones. The traveled surface of on-ramp terminal ends and adjoining speed change lanes were coated with a yellow reflective treatment consisting principally of minute reflective particles and associated binder applied by conventional pavement marking equipment and techniques. For maximum contrast with silver delineators customarily employed on through lanes and tangents, 50 cp/ft-c triple, yellow-amber delineators (dominant wave length 595m μ) were used on both sides of ramp and alongside the acceleration lane. Delineation and color treated surface of the acceleration lane was visible to through as well as on-ramp traffic.

Deceleration lanes and exit ramps together with relevant signs were similarly identified, using color to establish a relationship between signs, delineation, and roadway, thus simplifying the perceptual task. Search for a distinctive color not presently assigned other traffic control functions led to use of blue which has the additional advantage of providing maximum contrast with the complementary yellow of entrance locations. Required use of blue lighting and reflectorization for airfield taxiway and off-ramp guidance offers an analogous experience which, with similar experimental highway guidance applications elsewhere, suggests the use of blue in bifurcation treatment.

Application of the various reflective components incorporated into the cloverleaf interchange system is shown in Figure 1. Blue pavement areas represent reflectorized sections of exit roadway, paralleled by triple, blue delineators along ramps and deceleration lanes with blue guide signs pertaining to the adjacent exit. Yellow pavement areas represent reflectorized sections of entrance or merging roadways, paralleled by yellow delineation along ramps, acceleration lanes, and the right edge of the through highway preceding merging zones. Adjacent yellow signs are customary standard warning series. The remainder of through lane delineation was accomplished with conventional silver materials and traffic guidance, with standard green signs.

Interchange guidance information therefore is first presented to the approaching, north-bound motorist on conventional, green, 2-mi and 1-mi advance guide signs. Confirmation is subsequently provided by the color treatment as blue signs and delineation corresponding to the east-bound deceleration lane first appear, followed closely by the blue pavement treatment on approach areas, ramp surface and continuing with ramp delineation. Indication of merging lanes and identification of exit ramps to the north is similarly achieved by the distinction apparent between conventional through route markings, yellow at entrance points, and blue at exits. In the experimental Minnesota application, this treatment was installed on US 61 and the four appendant ramps at intersection with Minnesota 36 for the north-bound direction of travel. Abbreviated speed change lanes at this older interchange were sufficiently long to permit up to 150 ft of taper for test purposes. Roadway reflectorization covered these lanes and extended 200 ft up leg ramps from the nose, 150 ft for loop ramps. Conventinal 200-ft delineator spacing was used for the approach but decreased within the interchange to emphasize

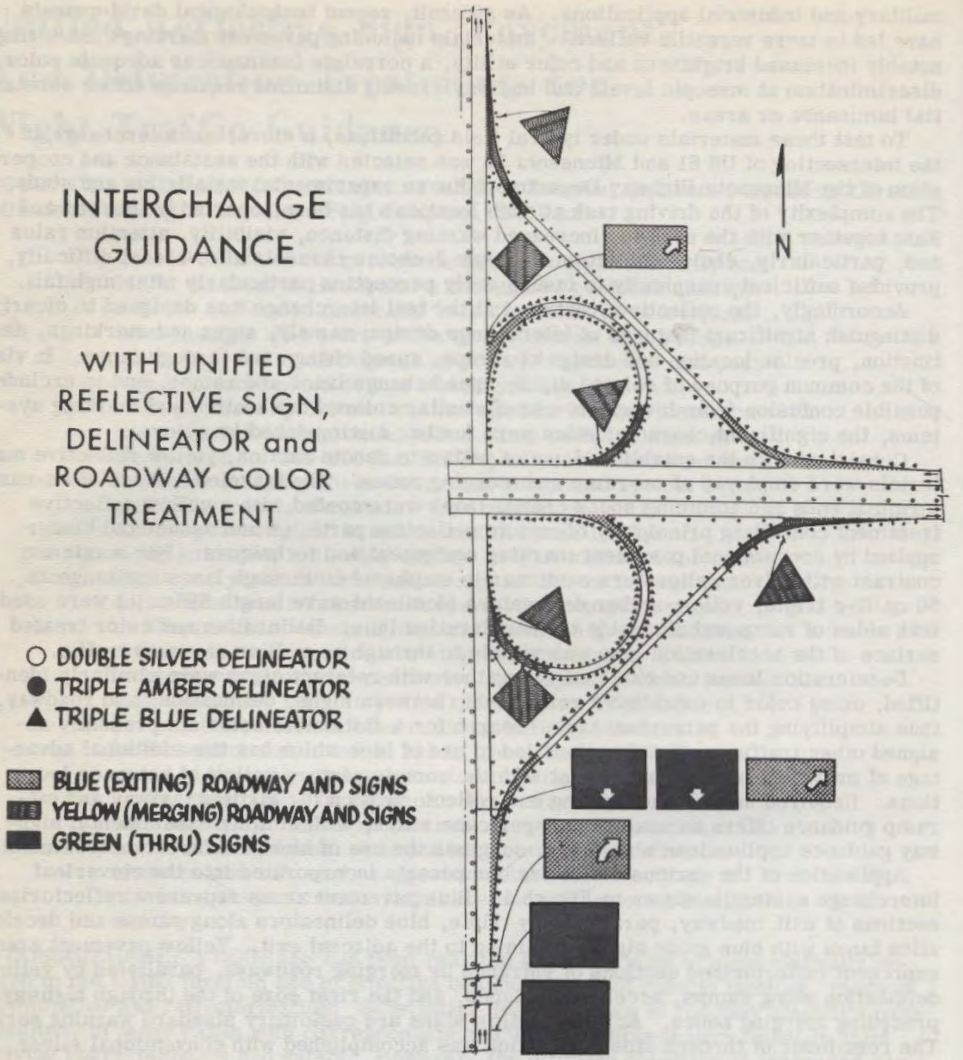


Figure 1. A unified reflective sign, delineator and roadway color treatment showing order of presentation for northbound traffic through a typical interchange. Similar systems may be employed in a number of related traffic guidance applications.

significant design features for effective distant perception. Within the interchange, 50-ft spacing was employed for through lanes, 25 ft for leg ramps and 15 ft for loop ramps, including connecting speed change lanes. Sign legend materials and sizes followed interstate standards with some legend modification in the absence of fully limited access or overhead sign structures (Fig. 2).

Previous use of reflectorized blue background signs in juxtaposition with green signs has led to some question of color discrimination. The dominant wave length of conventional blue reflective sheeting is approximately 495 mμ and peak reflectance 498 mμ compared to approximately 520 mμ for both in the case of the standard green. The similarity of hue (blue-green, green-blue) and possibility of confusion at night led to the develop-

ment of an attractive blue reflective sheeting with a peak reflectance deep in the blue end of the spectrum (475 mμ) and relatively high saturation in the red (620-700 mμ), resulting in a distinctive indigo-blue and subjective brightness similar to that of standard green.

Purity and reflectance of blue roadway treatment and delineators were similarly adjusted to provide dominant wave lengths of comparable value and sufficiently blue to be unmistakable (Fig. 3). Role and limited size of delineators together with reduced visual sensitivity to blue necessitated blue delineation of relatively high brightness. A construction of standard size resulted, with a characteristic value of 489 mμ and luminance of 6 cp/ft-c — a signal adequate to meet minimum long-range visibility requirements. Directional reflectance values for these retro-reflective components at representative



Figure 2. Night view of bifurcation treatment at exit ramp.

observation and incidence angles were established with a modified spectrophotometer. These are shown together with a 90 percent reflectance, diffuse white surface, relative to perfectly diffusing white.

Colored reflective roadway treatments are shown in terms of specific luminance (ft-l/ft-c) at divergence angles corresponding to viewing distances ranging from 1,000-80 ft (Fig. 4). Values are based on retro-reflective performance at representative entrance angles (88 deg) and exhibit initial efficiencies comparable to like-colored reflective sign materials and 20-500 X greater at applicable divergence angles than a hypothetical, 18 percent reflectance roadway surface. Relative to a perfectly diffusing, standard white surface, the brighter, yellow treatment increases luminance in the order of 65 X at 0.5 deg divergence, the blue 4 X.

Initial luminance of the treated road surface at 80 to 1,000 ft is shown relative to available headlamp illumination (Fig. 5). Upper and lower beam performance was derived from iso-candle curves based on representative output of the Dual Headlamp System (GE-4001 and 4002) and current headlamp-driver relationships, with vehicle centered in a straight, 12-ft lane. Luminance of right and left edges viewed with upper beams are identical for those distances considered. In view of lamp design features, lower beams understandably provide increased luminance at the right relative to the left edge.

Luminance of a conjectural 18 percent reflectance surface is illustrated as a standard of comparison with the treated roadway in establishing relative performance at all distances with upper and lower beams. Field measurements and limited published data

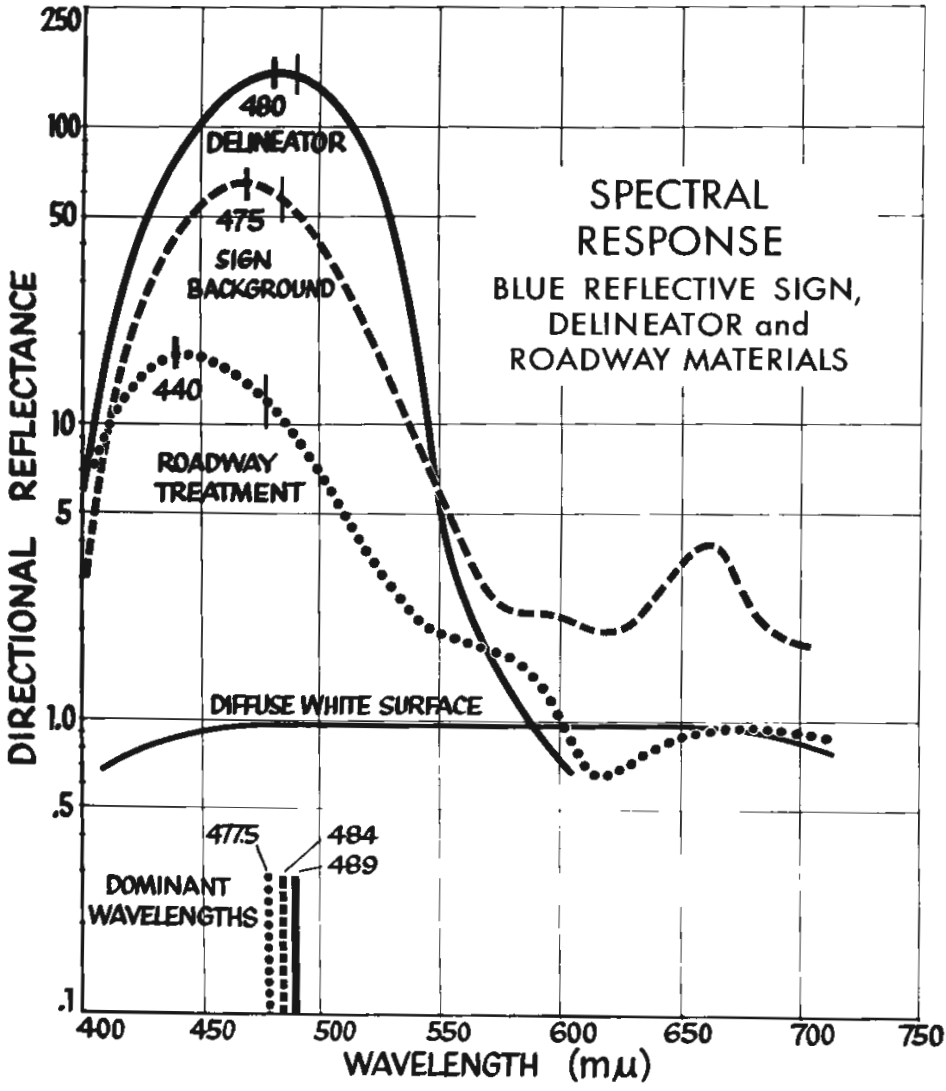


Figure 3. Spectral distribution of blue reflective signs, delineators and roadway marking materials shown relative to a diffuse white surface. Figures for spectral response at peak reflectance and dominant wavelength are given in millimicrons.

reveal typical pavement brightness illuminated with upper beams on the order of 0.08 foot-lamberts at 200 ft. At this distance with high beams, the reflective blue surface initially is shown to provide 6 foot-lamberts luminance, the yellow 40 ft-l, suggesting a 500-fold increase over a conventional pavement surface exhibiting 0.08 ft-l luminance. This relationship applies equally to wet surfaces in the case of those portions of the experimental application designed to perform wet or dry throughout their useful life, and appears independent of pavement texture.

Although the luminance of reflective pavement treatments is relatively independent

of pavement surface type, brightness is quite naturally a function of the projected pavement area. Horizontal ramp or speed change lane surfaces subtend a vanishingly small angle at distances greater than 1,000 ft. In addition, intersection surfaces may be temporarily covered with snow or ice or partially obscured by preceding vehicles, strongly establishing the warrant for supplementary delineation. The several reflective components may therefore contribute in varying proportion to the total perceptual purpose.

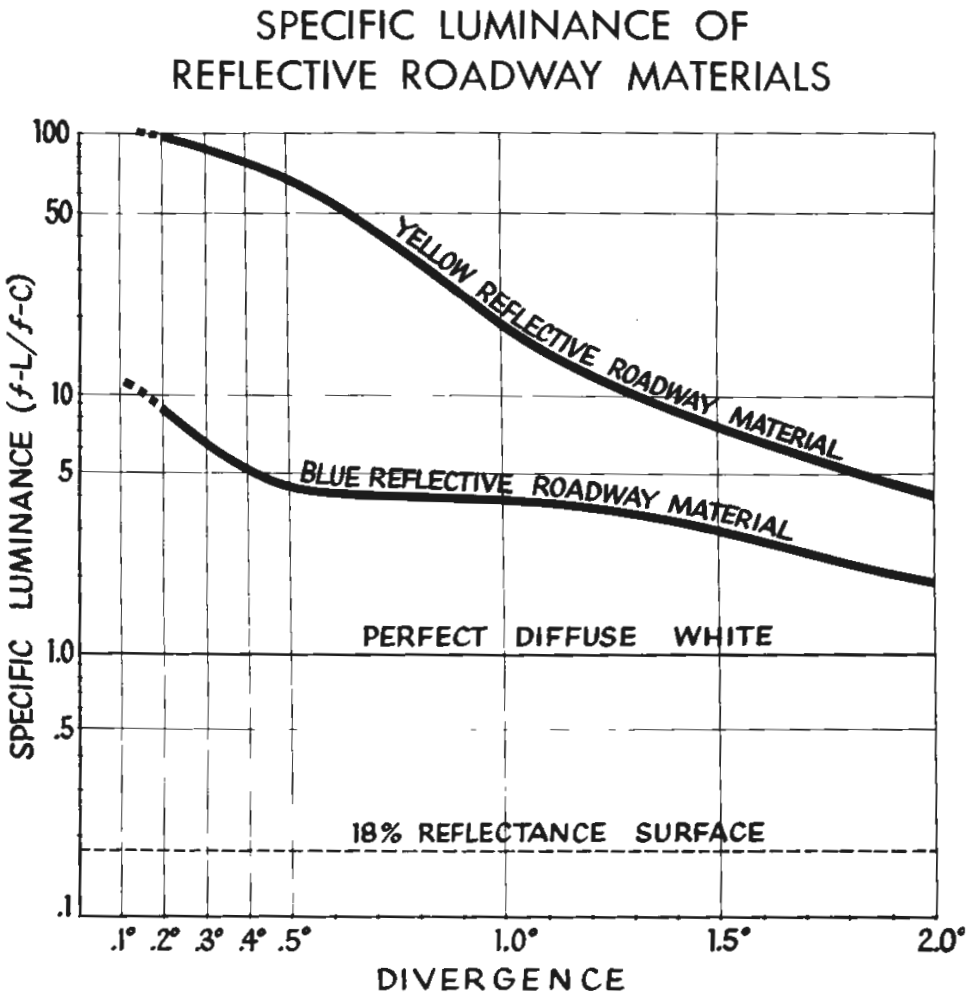


Figure 4. Specific luminance (foot-lamberts per foot-candle) of reflective roadway materials at divergence angles of 0.2 to 2.0 deg (approximately 1,000 to 80 ft). A diffuse surface exhibiting 18 percent reflectance and a perfectly diffusing white surface are shown for comparison.

Significant reduction of the perceptual impact through aberrant color deficiency is unlikely at the wave lengths in question. Frequency of tritans (blue-yellow deficient) has been found to be less than 0.008 percent in contrast with the more prevalent red-green

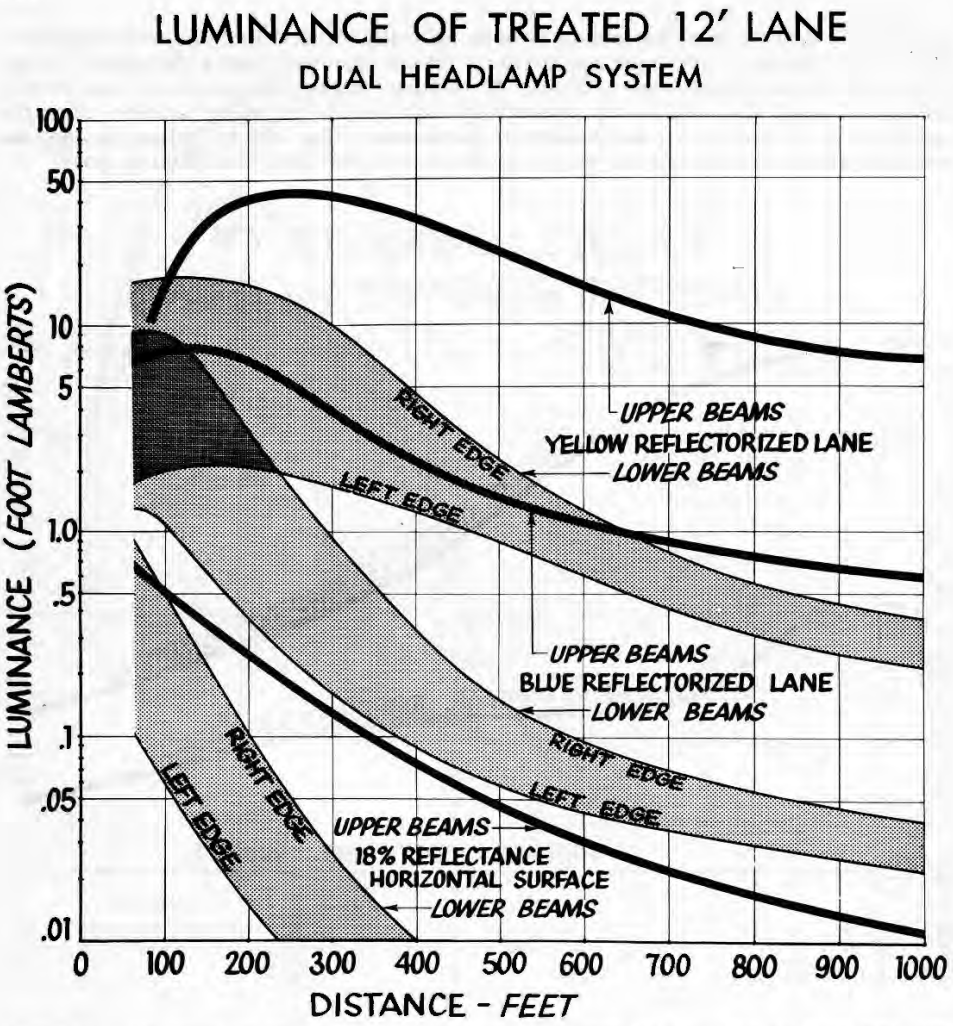


Figure 5. Luminance of treated roadway surface seen from 100 to 1,000 ft with Dual Headlamp System (G.E. 4001 and 4002) shown relative to an 18 percent reflectance roadway surface. Luminance of a straight 12-ft lane is shown from left to right for each color and upper and lower headlamp beams.

defectives. Their incidence has generally been found to be at least 2 percent of the adult population and the vast majority of this group are acutely perceptive of blue. Individuals deficient in ability to perceive yellow comprise the greatest rarities, suggesting that the complementary use of blue and yellow in this application offers the least likelihood of confusion, and provoking far less serious question than the color of traffic signal ware.

Choice of the particular location was largely dictated by the desirability of analyzing relative benefits of such treatment where established expressway traffic patterns and representative pavement surfaces, ambient illumination and lighting existed. Studies of driver attitudes, traffic characteristics and performance were undertaken in cooperation with the Traffic and Planning Division of the Minnesota Highway Department. These studies were conducted over a seven-week, midsummer period before and after

installation of the reflective color treatment and included, in turn, conventional delineation, modified interstate standard delineation and supplementary illumination.

It is not in the scope of this paper to report the results of these studies, however, the substance of completed work and expressions of other investigators suggest that valuable insight has been gained into the night visibility problem and effective techniques disclosed both for assessment and improvement of the perceptual element. Because all seeing depends on light, perception on contrast levels, and guidance on perception, effective guidance is dependent on both luminance and contrast. Intense retroreflective brightness, with contrast afforded by color as well as generally low background luminance, presages extensive new perceptual and guidance opportunities.

Color-keyed, reflective guidance systems should be restricted to readily distinguished hues and applications for maximum effectiveness. Indiscriminant color use may serve to defeat rather than enhance the effort to reduce driving complexity. Inasmuch as distinctive colors are limited, their application should be well considered, though not overlooked. Well conceived, unified reflective systems suggest a method that may effectively provide for the motorist's visual cue and guidance needs as well at night as by day.

ACKNOWLEDGMENT

The author is indebted to the Minnesota Department of Highways, and, in particular, J.E.P. Darrell and associates of the Division of Traffic and Planning for their assistance in making this study possible. He also gratefully acknowledges the counsel and extensive assistance of his associates in the Reflective Products Division Laboratory.

REFERENCES

1. "The Visual Factors in Automobile Driving." Armed Forces-NRC Committee on Vision, Nat. Acad. of Sci. Pub. 574 (1958).
2. Forbes, T.W., and Katz, M.S., "Summary of Human Engineering Data and Principles Related to Highway Design and Traffic Engineering Problems." Amer. Inst. for Research (April 30, 1957).
3. Technical Standard Order TSO-N3a, Administrator of Civil Aeronautics, Dept of Commerce (Oct. 15, 1946).
4. "Experiments with Colored Roads Increase." Quarterly Toll Review (Summer 1958).
5. Smith, C.G., "The Value of Coloured Road Surfaces." Highways and Bridges and Engineering Works (Sept. 17, 1952).
6. "Signing and Pavement Marking of the National System of Interstate and Defense Highways." AASHO Manual (1958).
7. Straub, A.L., and Allen, T.M., "Sign Brightness in Relation to Position, Distance, and Reflectorization." HRB Bul. 146 (1956).
8. Reid, K.M., and Chanon, H.J., "Determination of Visibility on Lighted Highways." Illum. Eng., 32 (1937).
9. Christie, A.W., "Reflection Characteristics of Pavement Surfaces." HRB Bul. 89 (1954).
10. Doane, H.C., and Rassweiler, G.M., "Cooperative Road Tests of Night Visibility Through Heat-Absorbing Glass." HRB Bul. 127 (1955).
11. Wright, W.D., "The Characteristic of Tritanopia." Jour. Opt. Soc. of Amer., 42: 8 (Aug. 1952).

APPENDIX C

National Cooperative Highway Research Program

Engn
S
N21
C88
346

RECEIVED
JUN 01 1992
UNIV. OF UTAH LIBRARY

NCHRP Report 346

Implementation Strategies for Sign Retroreflectivity Standards

Transportation Research Board
National Research Council

UNIVERSITY OF WISCONSIN - MADISON
LIBRARY

TRANSPORTATION RESEARCH BOARD EXECUTIVE COMMITTEE 1992

OFFICERS

Chairman: *William W. Millar, Executive Director, Port Authority of Allegheny County*
Vice Chairman: *A. Ray Chamberlain, Executive Director, Colorado Department of Transportation*
Executive Director: *Thomas B. Deen, Transportation Research Board*

MEMBERS

MICHAEL ACOTT, *President, National Asphalt Pavement Association* (ex officio)
GILBERT E. CARMICHAEL, *Federal Railroad Administrator, U.S. Department of Transportation* (ex officio)
BRIAN W. CLYMER, *Federal Transit Administrator, U.S. Department of Transportation* (ex officio)
JERRY R. CURRY, *National Highway Traffic Safety Administrator, U.S. Department of Transportation* (ex officio)
TRAVIS P. DUNGAN, *Research & Special Programs Administrator, U.S. Department of Transportation* (ex officio)
FRANCIS B. FRANCOIS, *Executive Director, American Association of State Highway and Transportation Officials* (ex officio)
THOMAS H. HANNA, *President and Chief Executive Officer, Motor Vehicle Manufacturers Association of the United States, Inc.* (ex officio)
BARRY L. HARRIS, *Acting Federal Aviation Administrator, U.S. Department of Transportation* (ex officio)
HENRY J. HATCH, *Chief of Engineers and Commander, U.S. Army Corps of Engineers* (ex officio)
THOMAS D. LARSON, *Federal Highway Administrator, U.S. Department of Transportation* (ex officio)
WARREN G. LEBACK, *Maritime Administrator, U.S. Department of Transportation* (ex officio)
GEORGE H. WAY, JR., *Vice President for Research and Test Departments, Association of American Railroads* (ex officio)
JAMES M. BEGGS, *Chairman, Spacehab, Inc.*
KIRK BROWN, *Secretary, Illinois Department of Transportation*
DAVID BURWELL, *President, Rails-to-Conservancy*
L. GARY BYRD, *Consulting Engineer, Alexandria, Virginia*
L. STANLEY CRANE, *former Chairman and CEO of CONRAIL*
RICHARD K. DAVIDSON, *Chairman and CEO, Union Pacific Railroad*
JAMES C. DELONG, *Director of Aviation, Philadelphia International Airport*
JERRY L. DEPOY, *Vice President, Properties & Facilities, USAir*
THOMAS J. HARRELSON, *Secretary, North Carolina Department of Transportation*
LESTER P. LAMM, *President, Highway Users Federation*
LILLIAN C. LIBURDI, *Director, Port Department, The Port Authority of New York and New Jersey*
ADOLF D. MAY, JR., *Professor and Vice Chairman, Institute of Transportation Studies, University of California, Berkeley*
WAYNE MURI, *Chief Engineer, Missouri Highway & Transportation Department* (Past Chairman, 1990)
NEIL PETERSON, *Executive Director, Los Angeles County Transportation Commission*
DELLA M. ROY, *Professor of Materials Science, Pennsylvania State University*
JOSEPH M. SUSSMAN, *JR East Professor of Engineering, Massachusetts Institute of Technology*
JOHN R. TABB, *Director, Chief Administrative Officer, Mississippi State Highway Department*
JAMES W. VAN LOBEN SELS, *Director, California Department of Transportation*
C. MICHAEL WALTON, *Paul D. & Betty Robertson Meek Centennial Professor and Chairman, Civil Engineering Department, University of Texas at Austin* (Past Chairman, 1991)
FRANKLIN E. WHITE, *Commissioner, New York State Department of Transportation*
JULIAN WOLPERT, *Henry G. Bryant Professor of Geography, Public Affairs and Urban Planning, Woodrow Wilson School of Public and International Affairs, Princeton University*
ROBERT A. YOUNG III, *President, ABF Freight Systems, Inc.*

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Transportation Research Board Executive Committee Subcommittee for NCHRP

WILLIAM W. MILLAR, *Port Authority of Allegheny County* (Chairman)
A. RAY CHAMBERLAIN, *Colorado Department of Transportation*
FRANCIS B. FRANCOIS, *American Association of State Highway and Transportation Officials*
THOMAS D. LARSON, *U.S. Department of Transportation*
C. MICHAEL WALTON, *University of Texas at Austin*
L. GARY BYRD, *Consulting Engineer*
THOMAS B. DEEN, *Transportation Research Board*

Field of Traffic
Area of Illumination and Visibility
Project Panel G5-11

KEN F. KOBETSKY, *West Virginia Department of Transportation* (Chairman)
J. TRAVIS BROOKS, *Federal Highway Administration*
GEORGE M. SMITH, *Michigan Department of Transportation*
J. RICHARD YOUNG, JR., *Mississippi State Highway Department*
JAMES I. TAYLOR, *University of Notre Dame*
MARGARET McINDOE LEWIS, *St. Marys County Department of Public Works, Maryland*
LEWIS R. RHODES, *Texas State Department of Highways*
JOHN J. LOGAN, *King County Department of Public Works, Washington*
JAMES L. PLINE, *Consultant, Boise, Idaho*
SAMUEL C. TIGNOR, *FHWA Liaison Representative*
RICHARD A. CUNARD, *TRB Liaison Representative*

Program Staff

ROBERT J. REILLY, *Director, Cooperative Research Programs*
LOUIS M. MacGREGOR, *Program Officer*
DANIEL W. DEARASAUGH, JR., *Senior Program Officer*
IAN M. FRIEDLAND, *Senior Program Officer*
CRAWFORD F. JENCKS, *Senior Program Officer*
KENNETH S. OPIELA, *Senior Program Officer*
DAN A. ROSEN, *Senior Program Officer*
HELEN MACK, *Editor*

National Cooperative Highway Research Program

Report 346

Implementation Strategies for Sign Retroreflectivity Standards

K. L. BLACK, H. W. McGEE and S. F. HUSSAIN
Bellomo-McGee, Inc.
Vienna, Virginia

Research Sponsored by the American Association of State Highway and Transportation Officials in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD
National Research Council
Washington, D. C. April 1992

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

Note: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers names appear herein solely because they are considered essential to the object of this report.

NCHRP REPORT 346

Project 5-11 FY'89

ISSN 0077-5614

ISBN 0-309-04869-9

L. C. Catalog Card No. 92-80551

Price $9.00

Areas of Interests

Operations and traffic control

Mode

Highway Transportation

UNIVERSITY OF WISCONSIN - MADISON LIBRARY

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

S
J21
C

AQA 2221
ADV 9525

FOREWORD

By Staff
Transportation Research Board

This report will be of interest to transportation officials concerned with the nighttime visibility of highway traffic signs and the cost for the replacement of signs to maintain a minimum standard of nighttime visibility. The report will be of particular interest to traffic engineers responsible for the management and maintenance of traffic signs. The focus of the report is retroreflectivity—the property of traffic signs that makes them visible at night. The key issue is the national cost to provide a given level of retroreflectivity as a function of the length of time over which the standard would be phased in.

In 1985, the Federal Highway Administration published an Advance Notice of Proposed Amendment to the *Manual on Uniform Traffic Control Devices* as the initial step in developing performance standards for in-service, retroreflective, traffic-control devices. Since then, research has been conducted to determine minimum visibility requirements for traffic signs that will satisfy the need of the nighttime driving population. In addition, research has been completed to develop cost-effective, field-measurement tools to determine whether a specific in-service traffic sign meets given retroreflectivity levels. Research on the service life of retroreflective signs has also contributed to the knowledge base needed to support the proposed establishment of retroflectivity standards.

However, before retroreflectivity standards can be implemented, their potential economic impact must be assessed. Further, any adverse effects of such standards should be mitigated. The research reported here was undertaken to provide alternative strategies for economical ways to improve the effectiveness of signs within available resources.

Under NCHRP Project 5-11, "Implementation Strategies for Sign Retroreflectivity Standards," research was undertaken by Bellomo-McGee, Inc., Vienna, Virginia, with the objective of determining the economic consequences of alternative standards for retroreflective traffic signs.

To accomplish the objectives, the research agency had to address the following questions:

- What is the status of the Nation's signs regarding their level of retroreflectivity?
- How many signs exist on the Nation's roadway system by sign type, jurisdictional level, and other key factors?
- What is the cost to replace signs by the type of sign, type of retroreflective material, and by jurisdictional location?

Once this information was obtained, an economic assessment model was applied with the following specific objectives: (1) Determine the economic consequences of

alternative standards for retroreflective traffic signs, i.e.: What will it cost to meet and maintain standards? (2) Develop economic-based implementation strategies and recommend options for systemwide implementation, i.e.: What are the alternative ways to have jurisdictions come into compliance, considering their resources?

The findings of the research have indicated that minimum retroreflectivity standards could cost approximately $156 million per year nationally for a 10-year implementation schedule under the higher of the two levels of standards evaluated. At the lower standards, the national cost would be no more than currently experienced for regular sign maintenance activities, assuming a 5- or 10-year implementation schedule. If a much shorter implementation schedule of one year was adopted, a one time cost of between $400 million and $2 billion would be expected, depending on the standards selected.

CONTENTS

1 SUMMARY

2 CHAPTER ONE Introduction and Research Approach
Project Background and Research Objective, 2
Scope of Study, 2
Research Approach, 3

3 CHAPTER TWO Findings
Literature Review Summary, 3
Summary of Retroreflectivity Data, 6
Summary of Questionnaire Survey, 7

10 CHAPTER THREE Interpretation, Appraisal, Application
Minimum Retroreflectivity Criteria, 10
Signs Requiring Replacement, 10
Sign Densities, 11
Sign Replacement Costs, 11
Implementation Strategies, 12
Inspection Program, 12
Sign Inventory Program, 13
Economic Analysis Methodology and Results, 13

18 CHAPTER FOUR Conclusions and Suggested Research
Conclusions, 18
Suggested Research, 18

19 APPENDIX A Literature Review

34 APPENDIX B Collection of Retroreflectivity Data

38 APPENDIX C Questionnaire Survey Results

40 APPENDIX D Sign Replacement Costs

44 REFERENCES

ACKNOWLEDGMENTS

The research reported here was conducted by Bellomo-McGee, Inc. (BMI) with Hugh W. McGee and Kent L. Black as co-principal investigators. Syed F. Hussain (BMI) conducted much of the statistical analyses with the support of Margaret Rouchon (BMI). Data collection and other technical assistance were provided by Justin J. Rennilson of Advanced Retrotechnology, Inc. (ATRI) located in La Mesa, California. Westat Inc. of Gaithersburg, Maryland, provided David Morganstein as a consultant for the development of the sampling plan followed in the collection of retroreflectivity condition of signs throughout the United States.

IMPLEMENTATION STRATEGIES FOR SIGN RETROREFLECTIVITY STANDARDS

SUMMARY

Minimum retroreflectivity standards for traffic signs are currently being considered and indications are that standards will be instituted in the near future. Prior to the establishment of retroreflectivity standards two key issues must be addressed: (1) how will the standards be implemented and (2) how much will the standards cost jurisdictions for replacement and maintenance activities. Currently, only new purchase specifications exist for permanent and temporary traffic signs. The retroreflectivity specifications measured in terms of specific intensity per unit area (SIA) are related to manufacturer's warranties and were not established based on motorist needs for sign legibility. Minimum retroreflectivity standards for traffic signs based on legibility requirements are needed.

Measurements of retroreflectivity were taken on approximately 8,000 traffic signs across the country. These samples became the basis for evaluating the general condition of the nation's traffic signs. A signing questionnaire was developed and distributed to state, county, and city jurisdictions. Estimates of sign inventory, replacement, and maintenance costs were derived from the survey responses. The Federal Highway Administration (FHWA) supplied ranges of minimum retroreflectivity values for this project. Lower and upper sets of retroreflectivity values were selected from the FHWA data for red, yellow, green, and white sheeting. The number of signs not meeting the standard criteria was determined for each sheeting type. The economic costs associated with the necessary sign replacement and related maintenance activities were determined. Several implementation strategies and schedules were identified for instituting the minimum retroreflectivity standards. These include prioritizing sign replacement by sign type and roadway class. Implementation schedules ranged from 1 to 10 years for compliance. Because a broad economic analysis was required only basic implementation strategies were tested. These strategies assumed no prioritization of sign or roadway types, but required compliance with the standards within 1 to 10 years.

The current national population of traffic signs (not including street name and parking) is estimated to be nearly 60 million. If the higher minimum retroreflectivity standards tested in this research were applied, approximately 17 million traffic signs on the nation's roadways would require replacement today. This would amount to approximately $156 million in sign maintenance costs per year for a 10-year implementation program. If the lower standards were applied, the cost for maintenance activities should not exceed current expenditures with a 5- or 10-year implementation schedule. With the advent of retroreflectivity standards, jurisdictions will also have to consider instituting sign inventories and strict inspection programs. These items will create an additional monetary demand on signing budgets. Preliminary results of an on-going FHWA research project dealing with motorists' needs in relationship to sign legibility were used to develop the minimum retroreflectivity standards tested here.

The research found that the economic impacts of standards will be hardest felt by city jurisdictions. This is because of the relatively poor condition of traffic signs on city roadways. In addition, deficient green signs accounted for a disproportionate share of replacement costs across all jurisdiction types. Green sheeting, especially engineering

grade, has rather low retroreflective properties. One of the minimum standards tested here for green sheeting was actually higher than the delivered new specification prescribed by states and the FHWA for engineering grade sheeting. Ground-mounted guide signs also tend to be at least twice as large as standard warning and regulatory signs; therefore, the cost to replace ground-mounted guide signs is nearly double that of other traffic signs.

The research reported here tested two sets (i.e., lower and upper) of retroreflectivity standards. The lower standards should have minimal economic impacts on most jurisdictions. However, the upper standards would have an extreme impact on signing budgets. Maintenance to the upper standards could cost two to six times as much as current budgets. The establishment of retroreflectivity standards between the two sets of standards tested here would still burden some jurisdictions. However, the anticipated benefits of reduced liability and improved public safety could offset the additional maintenance costs.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

PROJECT BACKGROUND AND RESEARCH OBJECTIVE

Traffic signs are a very important component of streets and highways. They help motorists find their way in a safe manner by providing for the orderly and predictable movement of traffic. For signs to accomplish their intended purposes, they must be visible to the motorists. Although sign visibility is generally not a problem during daylight, signs with inadequate retroreflectivity may not be sufficiently visible at night and can contribute to accidents.

Research has been initiated to determine visibility requirements for traffic signs that will satisfy the needs of the nighttime driving population. In addition, research is under way to develop field measurement tools to determine whether a specific in-service traffic sign meets given retroreflectivity levels.

The Federal Highway Administration (FHWA) published an Advanced Notice of Proposed Amendment (*1*) to the *Manual on Uniform Traffic Control Devices* (MUTCD) (*2*) as an initial step in developing a performance standard for in-service retroreflectance of traffic control devices. The principal behind such a standard is that signs and other devices that rely on internal retroreflectance to be visible should maintain a level of performance that relates to minimum driver visibility requirements. This objective is not without technical, logistical, and practical obstacles.

One critical technical issue to resolve is to establish driver nighttime visibility needs and translate those to sign retroreflectivity requirements. This has been the task of a FHWA project entitled, "Minimum Visibility Requirements for Traffic Control Devices." The primary objective of that project is to develop a relationship between retroreflectivity levels and driver profiles so that in developing a performance standard one can use as a criterion the percent of drivers excluded by the standard.

Another issue, which is both technical and logistical, is the field measurement of retroreflectivity for signs and other devices. If the performance standard is to be a minimum retroreflectivity value, an easy method for measuring this property of in-service signs is required. The current method is to use a portable retroreflectometer. The most prevalent apparatus used is the Model 920™ manufactured by Advanced RetroTechnology, Inc. While this is a portable unit, it is still felt too cumbersome and time consuming to be used for a wide scale inspection program. The National Cooperative Highway Research Program (NCHRP) Project 5-10, "A Mobile System for Measuring Retroreflectance of Traffic Signs" (*3*) has resulted in a prototype system that is under further evaluation and refinement by FHWA.

On the practical side, there is the issue of what will be the economic impact imposed on the various jurisdictions, and indeed the public, of establishing a performance standard. Depending on the strictness of the standard, i.e., the retroreflectivity level and how soon the jurisdictions would have to be in full compliance, there will be an initial financial impact of replacing the existing deficient signs and devices. Thereafter, there will be a continuing cost to maintain the entire system within the prescribed standard. Before establishing the performance standard, the FHWA and others faced with this decision should be aware of what these impacts would be for different standard levels. How many signs would have to be replaced, what would be the costs to do so, and what will it cost agencies to maintain the signs to the standard? These and other related issues are addressed by this project.

SCOPE OF STUDY

The performance standard has not yet been established and it was not the objective of this study to do so. Rather, it was the

objective of the NCHRP Project 5-11 to assess the impacts of alternative standards and provide strategies and guidelines for implementing the standard.

Before sign retroreflectivity standards can be implemented, their potential economic impact must be assessed and any adverse effects of such standards should be mitigated. To meet the overall objective of this study, and to resolve these issues, requires certain information. The information includes: What is the status of the Nation's signs regarding their level of retroreflectivity? How many signs exist on the Nation's roadway system by sign type, jurisdictional level, and other key factors? What is the cost to replace signs by the type of sign, type of retroreflective material, and by jurisdictional location?

This information is required to meet the specific objectives of this project. The information must be analyzed within an economic model to determine what it will cost jurisdictions to replace signs that do not meet alternative standards. The specific objectives, therefore, are as follows: (1) Determine the economic consequences of alternative standards for retroreflective traffic signs, i.e., What will it cost agencies to meet and maintain standards? (2) Develop economic-based implementation strategies and recommend options for system-wide implementation, i.e., What are the alternative ways to have jurisdictions come into compliance considering their resources?

It was anticipated that the initial costs of compliance with retroreflective standards would be substantial and beyond the resources of many jurisdictions. Alternative strategies for implementing the standards need to be identified and evaluated.

RESEARCH APPROACH

To accomplish the goals and objectives of this project the following general tasks were completed:

Task 1—Evaluate Literature and Other Sources. The literature and other informational sources dealing with retroreflectivity of traffic signs were considered. The various types of sign inventory systems in use and current maintenance practices were investigated.

Task 2—Summarize Information Pertinent to Establishing Feasibility Retroreflectivity Standards. This task was accomplished by reviewing pertinent references and by considering the latest results and findings from on-going and recent research projects.

Task 3—Collect Retroreflectivity Condition and Other Sign Data. Existing data on in-service sign retroreflectivity, replacement costs (e.g., labor and material), and sign densities were collected and compiled. Data were collected on standard, ground-mounted traffic signs. Overhead and parking series signs were not included.

Task 4—Analyze Data. For different categories of signs, relationships were developed that indicate how various retroreflectivity standards would affect, nationally and at the state and local levels: (a) the number of signs to be replaced, (b) the replacement costs, (c) any other economic or management considerations. The modeling techniques used are described so they can be applied readily to any jurisdiction's sign replacement and management programs.

Task 5—Develop Economic-Based Implementation Strategies. Economic-based implementation strategies were developed for alternative sign retroreflectivity standards across different categories of signs, roadways, and jurisdictions.

Task 6—Recommended Implementation Options. Several options for system-wide implementation were developed to provide guidance for phasing the implementation of the retroreflectivity standards and to indicate the expected economic consequences of adoption of the standards.

CHAPTER TWO

FINDINGS

This chapter presents the key findings of the study in three sections. Specifically, these sections relate to the literature review, the retroreflectivity data collected from more than 8,000 sign samples across the country, and the results of the questionnaire sent to the states, counties, and cities for information, sign inventories, and maintenance. More detailed information is provided in Appendixes A, B, C, and D.

LITERATURE REVIEW SUMMARY

Principles of Retroreflection and Sheeting Materials

Nearly all signs have to be legible and color distinguishable at night as well as day. While this can be accomplished through external illumination of the signs, retroreflection is the most commonly used means of making signs visible to the driver at night.

Retroreflection occurs when light rays strike a surface and are redirected back to the source of light. Two principles followed to achieve retroreflectivity for roadway signs are prismatic and spherical lens retroreflection. Prismatic, also known as cube-corner, retroreflection is achieved through total internal reflection. Incoming light hits the first surface and reflects to the rear surface which reflects it to the last surface which reflects the light rays back to the source. In the second type, spherical lens retroreflection is achieved through a combination of a glass sphere (bead) and a reflecting (mirror type) surface placed at the focal point. The incoming ray is bent and directed inside and toward the back of the sphere, reflecting off reflective surface, and after being bent at the exterior of the sphere redirected

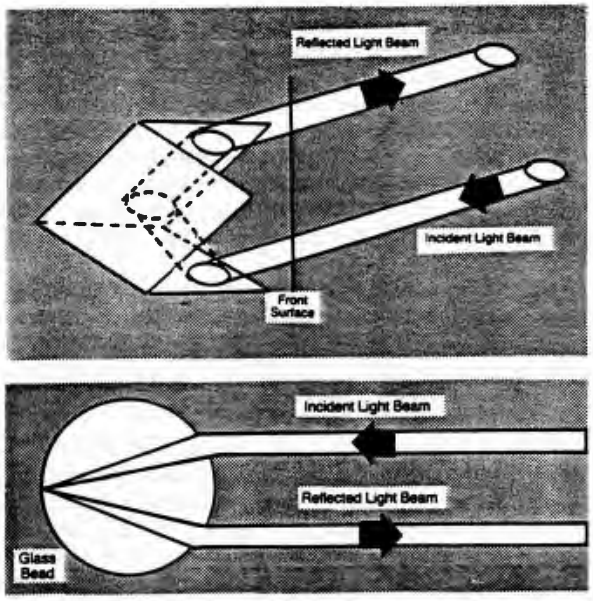


Figure 1. Two types of retroreflection, cube-corner (top) and spherical lens (bottom).

toward the light source. These two principles for achieving retroreflection are illustrated in Figure 1 and further described in Appendix A with the entire literature review. Three references (*4,5,6*) are suggested for a thorough discussion of the principles of sign retroreflectivity.

Retroreflective sheeting consists of micro cube-corners or spheres enclosed in a weather resistant, transparent plastic film. To reflect color, pigment or dye is inserted into the film or on the reflecting surface. There are three types of spherical lens (bead) retroreflective sheeting: (1) exposed glass bead, (2) enclosed glass bead, and (3) encapsulated glass bead. In the exposed lens sheeting the front half of the glass beads are exposed to the outside air. Glass beads work best when exposed to the air. However, because of the small size of the beads, a film of water can cover the beads when it rains and can greatly reduce the retroreflectivity of the beads. Hence, this type of sheeting is not recommended for traffic signs and is no longer included in state or federal specifications. Nonetheless, exposed lens sheeting is still found on traffic signs on some low-volume rural roads controlled by local jurisdictions.

Enclosed lens sheeting material consists of a layer of transparent plastic of appropriate color in which glass beads are imbedded. A metallic reflection shield is provided behind the plastic, with a layer of adhesive and with a protective liner that is removed during sign fabrication. The plastic covering enables the sheeting to be equally bright under dry and wet weather conditions.

With encapsulated lens sheeting the glass beads are also protected by a transparent material that is supported slightly above the beads by walls creating an air-filled compartment. The back of the beads are covered with a reflective surface. The resulting airspace in front of the beads makes it more retroreflective and, hence, is known as high performance sheeting.

One of the most important properties of retroreflective sheeting is the ability to return light that is commonly described by a variety of terms including brightness, retroreflectance, luminance, and candlepower. The International Commission of Illumination (CIE) uses the term coefficient of luminous intensity that is defined as the ratio of luminous intensity of reflector in the direction of the observation to the illumination at the retroreflector on a plane perpendicular to the light. In the metric system, designated as the International System of Units (SI), it is expressed as candelas, cd, per lux, lx. This definition treats the retroreflector as a point source. Because signs have a relatively large area, they are treated as an extended light source which may be thought to consist of many point sources, each with a luminance intensity of one candela. The coefficient of luminous intensity divided by the area is expressed in SI units as candelas per lux per square meter and identified as the coefficient of retroreflection. The English equivalency for coefficient of retroreflection is candelas per foot candle per square foot and is denoted as R_A. In the *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, FP-85* (*7*), the coefficient of retroreflection, R_A, is described as specific intensity per unit area (SIA). The conversion from SI to the English system is unity. CIE plans to adopt R_A as their designation in the SIA nomenclature. The SIA designation will be used throughout this report.

The retroreflectance of sheeting material is described in the context of another important property, its angularity, which is defined by the entrance (of the light) and the observation (of the motorist) angles. The entrance angle is the angle formed between a light beam striking the surface of a sign and a line coming out perpendicular from the surface. The observation angle is the angle between the incoming light beam and the reflected light beam and is a function of the height of the driver's eye with respect to the vehicle headlamps. In the FP-85 and other specifications, minimum SIA is prescribed for each different type of sheeting for two observation angles, two entrance angles, and for different colors.

The following specifications, related to retroreflectance, were a primary source of information:

1. *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, FP-85* (*7*).
2. Federal Test Method Standard 370, Instrumental Photometric Measurements of Retroreflective Materials and Retroreflective Devices (*8*).
3. Four standards of the American Society for Testing and Materials (ASTM) on color and appearance measurement:

- E808-81 "Standard Practice for Describing Retroreflection"
- E809-81 "Standard Practice for Measuring Photometric Characteristics of Retroreflectors"
- E810-81 "Standard Test Method for Coefficient of Retroreflection of Retroreflective Sheeting"
- E811-81 "Standard Practice for Measuring Colorimetric Characteristics of Retroreflectors Under Nighttime Conditions"

In the FP-85, three types of retroreflective sheeting are recognized. The first type has two classes: Type II and Type II A, commonly called engineering and super-engineering grade sheet-

ing, respectively. They are both enclosed-lens type sheeting. The minimum SIA values specified by FP-85 for Type II A are about twice those for Type II. The next type has three classes: Type III A, III B, and III C. All are encapsulated type sheeting with Type III A made of glass beads and Type III B and III C made of prismatic reflectors. All three types provide much higher brightness than both Type II and Type II A. The last type of sheeting recognized in the FP-85 is labeled as Type IV. This type is a high performance vinyl sheeting that is used for retroreflective white collars around orange cones and for "fold-up" temporary signs of the kind commonly used by utility companies.

Visibility Distance

The sight distance requirement of a sign is a function of five components: (1) sign detection, (2) sign recognition, (3) driver decision-making, (4) response, and (5) completion of maneuver. McGee et al. (*9*) developed and field tested a decision sight distance model based on detection, recognition, decision-making, response, and vehicle maneuver. The decision sight distance model elements were later reexamined by Perchonok et al. (*10*) to develop a version applicable to determining nighttime visibility requirements for retroreflective devices. The model determines minimum detection distance requirement as the summation of distances required for five phases of action. The summation process is based on the assumption that, in the worst case, the driver must accomplish each aspect of the process in order, one after the other. The model was formalized by Mace et al. (*11*) as a computerized program to evaluate luminance requirement to aid in sign maintenance decisions. This sign maintenance management program models sign visibility requirements in terms of time and distance requirements. However, it does not model the visibility requirements of signs based on human performance capabilities in terms of luminance and contrast needs.

The human visual performance model most generally accepted among highway visibility researchers is that published by the International Commission on Illumination (CIE). This model represents an analytic approach to determining the observer's detection threshold contrast when adapted to a particular surround luminance, with glare and transient adaptation requirements accounted for. An object is visible or detectable at threshold level if the object's contrast meets or exceeds the contrast required by an observer when adapted to the luminance of the object's background, also taking into account the effects of disability glare and background luminance that may change over time. This analytic approach to visibility has been incorporated by Bhise et al. (*12*) into a seeing distance model called DETECT, which is a part of the Comprehensive Headlamp Environment Systems Simulation Model (CHESS). The program calculates the threshold visibility distance (50 percent probability of detection) to targets such as delineation, pedestrians, traffic cones, etc., under a wide range of conditions with or without glare from opposing vehicles.

Sign Legibility

Drivers require a minimum amount of luminance for detection and legibility of signs. The specification of minimal luminance requirements for traffic signs has been addressed by a number of researchers. Historically, a sign was considered sufficiently bright if it provided approaching drivers with a minimum of 50 ft of legibility per inch of letter height. However, the selection of 50 ft per in. as a minimum legibility distance is quite arbitrary. Mace (*13*) suggested that older driver's visibility requirements should be based on a legibility of 40 ft per in. of letter height. Mace also reported that the typical practice in the states is to license drivers at a 20/40 high-luminance acuity. This acuity level corresponds to a legibility of approximately 30 ft per in. of letter height.

An approach that has been used is to consider a sign's level of brightness. Sign brightness is considered satisfactory if it provides a legibility distance that is greater than or equal to 85 percent of the maximum obtainable nighttime legibility distance. This criterion is too arbitrary as it does not account for the driving situation.

Other measures that have been used to develop the relationship between sign brightness and legibility have been uniformity of sign background, level of internal contrast, and luminance of legend or background. If a sign face degrades unevenly as it ages, the legibility of the sign is impaired. The Institute of Transportation Engineers (ITE) recommends a ratio of 5 : 1 as the maximum acceptable ratio of luminances for externally lighted traffic signs (*14*). Another study conducted by Allen et al. (*15*) concluded that variation in the luminance of different areas of the sign should not be more than 10 : 1. Another study (*16*) specifically designed to establish the relationship between the luminance uniformity of sign background and legibility found that for externally illuminated signs these two variables are significantly correlated only when sign luminance ranges from 9.9 to 39.7 foot-lambert (FL). These data indicated that if a reduction in maximum obtainable legibility of 50 percent is assumed to be maximum acceptable performance decrement, the maximum acceptable ratio of background luminances is 6 : 1. However, the luminance of Type II and Type III white sheeting rarely exceeds 9.9 FL. For these reasons, the luminance uniformity of background may be relevant to legibility of illuminated signs, but may not be relevant to retroreflective signs.

The contrast between the luminance of the sign legend and the luminance of the sign background is a key measure that has been related to sign brightness and legibility. A common measure of internal contrast is the luminance ratio of the legend and background of the sign, with the greater of the two values used in the numerator of the expression. For signs with a black legend on color background the legibility is determined by the luminance of the color portion of the sign. Therefore, minimum brightness standards based solely on internal contrast would have little applicability to signs having either a black legend or a black background. Also, most signs will not be taken out of service until they have lost most of their retroreflectivity, which means that the internal contrast of the sign is essentially fixed for the duration of the sign's service life by the material with which it is constructed. Therefore, internal contrast is most relevant in sign design and construction.

Another measure of sign brightness that can be related to legibility is sign luminance. Legibility as a function of sign luminance has been studied to a greater extent than any other measure of sign brightness. A 1988 study of nighttime conspicuity of highway signs by Olson (*17*) resulted in recommendation of minimum SIA values for various sign types with guidance re-

Table 1. End of service life SIA values recommended by Florida DOT.

Sheeting Color	End of Service Life SIA Values[1]	
	Type II[2]	Type II A, III A, III B[3]
White	40	140
Yellow	16	40
Green	5	5
Red	na	10

na - not available

[1] SIA values measured at 0.2° observation and -4° entrance angles.
[2] Engineering grade sheeting (Type II).
[3] Super-engineering grade (Type II A), high performance (Type III A), and prismatic (Type III B) sheeting.

Source: Florida DOT (19)

garding the selection of sheeting materials. The SIA values are based on area complexity and the required stopping sight distances for various speeds.

Another study by Morales (*18*) resulted in recommendation on required overall SIA for STOP signs for various approach speeds under ideal visibility conditions. The study suggests that legibility should not be used as a criterion for developing in-service retroreflective standards for STOP signs, and it provides mathematical relationships between STOP-sign recognition distance and its photometric characteristics. This is because the unique shape of STOP signs should be recognized and not read to be understood.

A study conducted by the Florida DOT (*19*) recommended "end of service life" SIA values for various sheeting colors and types. The study used several observers, at night, in the same vehicle. Each observer recorded when sign detection, shape recognition, color recognition, message recognition and legibility occurred. The times were converted to distances. Each sign was then screened, thereby reducing SIA, until the sign was determined to be barely adequate. Table 1 provides the recommended "end of service life" values for white, yellow, green, and red sheeting colors.

Luminance Standards

The existing federal standards for luminance of retroreflective materials for traffic signs are purchase specifications and provide no differentiation based on driver needs. The MUTCD (*2*) simply specifies that all warning and regulatory signs be reflectorized or illuminated to show the same color and shape by day or night unless specifically excepted in the standards. The MUTCD has no minimum initial or replacement requirements for retroreflective signs. FP-85 does provide minimum SIA standards for new material. These standards, however, were developed by sheeting manufacturers as a purchase specification not based on driver's needs. For work zone traffic control, FP-85 (*7*) does specify that traffic signs and devices must retain 75 percent and 50 percent of the new specification for engineering grade and high performance sheeting, respectively.

Based on the agencies surveyed, replacement is left to practices that vary between states and levels of government within states. The need for inspection of signs for retroreflectivity is typically not determined under a regimented policy or schedule, but is by casual, visual inspection. This deficiency is due to the lack of a minimum brightness standard, the competing demands on personnel's times, and the absence of a rapid and reliable reflectance measurement device. However, the development of automated sign inventories, minimum performance standards, mobile system for measuring retroreflectance, and implementation strategies will provide an opportunity for more efficient and objective solutions to the problems of sign maintenance management.

Research has been conducted which is relevant to the question of a standard, but standards have not yet been implemented that reflect fundamental driver needs. This is because specifying luminance standards for traffic signs is complex and multidimensional. Driver requirements of different signs change across situations. Also the population of signs is not uniform in purpose or function. Signs are created in different designs to serve various needs, and these differences create varying levels of luminance required for signs to function properly at night.

The FHWA project on "Minimum Visibility Requirements for Traffic Control Devices," is to determine the minimum visibility distances for signs and markings. Based on these minimum visibility requirements, it will be possible to determine the retroreflectivity necessary to make a sign or marking visible at a given distance. Another difficulty in the implementation of standards has been an absence of conclusive performance data. The final report for that project will fill this void.

The FHWA project entitled "Service Life of Retroreflective Traffic Signs" (*20*) investigated the relationship between the retroreflectivity performance of sign sheeting with respect to such factors as age, weather conditions, and the like. Based on these relationships, equations were developed to predict approximate in-service SIA of signs. The accuracy of the equations in predicting in-service SIA is limited, however, because the initial SIA values for new sheeting are quite variable.

Finally, there is no fast, practical and reliable way of measuring luminance in the field and, therefore, one cannot easily determine if the requirements are met. The study conducted under NCHRP Project 5-10, "Mobile System for Measuring Retroreflectance of Traffic Signs" (*3*), has determined the feasibility of developing instrumentation suitable to rapidly measure retroreflectivity from a moving vehicle during daylight hours. A prototype of the van-mounted system has been constructed and consists of a video camera, electronic flash gun, laser range finder, and a data acquisition/image analysis system to evaluate the video image for average legend and background retroreflectance. The results of the above three projects and the project reported here will help in development, measurement, and implementation of sign performance standards.

SUMMARY OF RETROREFLECTIVITY DATA

This section provides a summary of the retroreflectivity data collected from more than 8,000 sign samples. The 8,000 signs were samples from roadways within 28 counties in 26 states. The data collection procedures and methodologies are described in Appendix B. Table 2 presents a breakdown of total samples by sheeting color, sheeting type, and area type.

As shown in Table 2, a reasonable sample of each sheeting color and type in urban and rural areas was obtained. Not unexpected was the relatively low sample of high performance green sheeting. Apparently, few agencies currently use high perform-

ance green sheeting on their ground-mounted guide signs. Overhead signs were not included in the survey.

SIA data were collected from signs on roadways under the control of state, county, city, and town agencies. Table 3 presents the minimum, maximum, and mean SIA values for each sheeting color, sheeting type, and jurisdiction control. Except for high performance green sheeting, a reasonable sample within each jurisdiction type was obtained. As presented, differences in mean SIA values between jurisdictions do exist.

To facilitate the testing of the impacts of implementing minimum SIA standards, frequency graphs of SIA versus percent of total signs were developed. As the minimum SIA standard will be based on driver's needs and not sheeting material specifications, the sheeting types were combined by sheeting color for development of the frequency graphs. Because the intent of this project was to evaluate the economic impacts on various levels of jurisdictions, individual frequency graphs for state, county, city, and town agencies were developed. SIA values were grouped into increments of 5 SIA values and plotted versus percent of total samples. The graphs depict the percent of signs having that specific SIA value or less.

Figures 2, 3, 4, and 5 provide the frequency graphs for red, yellow, green, and white sheeting, respectively. Again, these graphs include all sheeting types combined and are provided for each of the four jurisdiction levels evaluated. Few conclusions about maintenance practices can be drawn from the frequency graphs. However, it does seem that traffic signs on city-controlled roadways tend to have lower retroreflectivity values across all sign colors.

SUMMARY OF QUESTIONNAIRE SURVEY

A survey concerning sign inventories, maintenance costs, and density factors was distributed to 790 counties, 85 cities, and 50 states. The full results of the questionnaire survey are presented in Appendix C. The major findings are presented here.

Approximately 30 percent of the states responding (48 total responses) maintain a sign inventory at the statewide or district level. Because the questionnaire survey was not inclusive of all agencies an accurate estimate of the percentage of cities and counties having sign inventories is unavailable. It is assumed, however, that few (i.e., 10 to 25 percent) of these local agencies maintain inventory systems. Table 4 provides a summary of inventory systems and data elements for city, county, and state agencies.

Of the states with sign inventories, approximately 80 percent have their systems on micro- or mainframe computers. Only 50 to 60 percent of the local jurisdictions with sign inventories maintained them on a computer system. Almost 50 percent of county agencies with inventories responded as having paper records. Nearly all inventories had the MUTCD sign type designation as a field in the system. Approximately 50 percent of the inventory systems included fields for the sheeting type. But, 75 to 85 percent of the inventory systems did include fields for the date of sign installation or replacement.

Table 5 provides a summary of sign costs and a listing of key reasons for sign replacement. Fabrication includes costs for materials, labor, and equipment. The counties responding to the survey estimated a fabrication cost of approximately $68.00 per sign, while the cities responding estimated a fabrication cost of approximately $54.00 per sign. The major differences were generated by the higher material and labor costs reported by county agencies. City-controlled roadways typically have much higher sign densities than county roads. Because of these differences, annual sign maintenance costs per mile on city roadways were 45 percent greater than that on county roads. However, the annual sign maintenance costs per capita were only 20 percent higher in city jurisdictions.

Concerning reasons for sign replacement, several differences between the city and county responses were found. The cities

Table 2. Total sample by area type.

Sheeting Color and Type	Urban	Rural	Combined
RED			
-EG	500	392	892
-HP	311	221	532
YELLOW			
-EG	594	635	1,229
-HP	608	511	1,119
GREEN			
-EG	209	178	387
-HP	61	23	84
WHITE			
-EG	1,293	996	2,289
-HP	798	676	1,474
TOTAL	4,374	3,632	8,006

NOTE: EG = Engineering Grade Sheeting = 60% of sample
HP = High Performance Sheeting = 40% of sample

Table 3. Description of retroreflectivity data.

Sheeting Color and Type	Criteria	Jurisdiction Type				Combined
		State	County	City	Town	
Red - EG	Min[1]	1.5	2.9	1.0	0.8	0.8
	Max[2]	55.4	59.0	55.2	55.6	59.0
	Mean[3]	19.3	19.7	15.4	18.3	17.6
	N[4]	177	222	365	128	892
Red - HP	Min	9.7	4.5	5.8	13.4	4.5
	Max	110.1	109.6	105.7	105.9	110.1
	Mean	51.1	58.2	64.5	68.3	60.1
	N	138	143	142	109	532
Yellow - EG	Min	1.5	1.1	2.2	7.9	1.1
	Max	136.5	147.1	121.0	137.6	147.1
	Mean	67.4	68.0	58.0	78.7	67.5
	N	352	488	217	172	1,229
Yellow - HP	Min	5.9	4.0	106.5	116.2	4.0
	Max	259.3	254.3	249.8	251.5	259.3
	Mean	192.1	186.8	192.7	193.7	190.4
	N	411	421	134	153	1,119
Green - EG	Min	0.6	1.0	1.9	6.1	0.6
	Max	48.6	50.2	31.6	35.5	50.2
	Mean	12.7	14.2	11.7	12.7	12.9
	N	227	85	42	33	387
Green - HP	Min	12.5	11.1	54.1	13.5	11.1
	Max	80.5	79.0	74.6	37.5	80.5
	Mean	47.2	44.2	64.5	27.4	46.1
	N	60	14	4	6	84
White - EG	Min	1.4	1.6	1.2	2.6	1.2
	Max	147.8	150.2	143.6	147.1	150.2
	Mean	89.9	92.5	75.9	98.5	88.2
	N	666	606	633	383	2,289
White - HP	Min	48.0	33.4	113.0	182.5	33.4
	Max	339.1	331.3	326.7	333.6	339.1
	Mean	271.1	271.8	272.9	281.4	273.4
	N	532	424	261	257	1,474

[1] Minimum SIA [3] Mean SIA
[2] Maximum SIA [4] Number of Samples

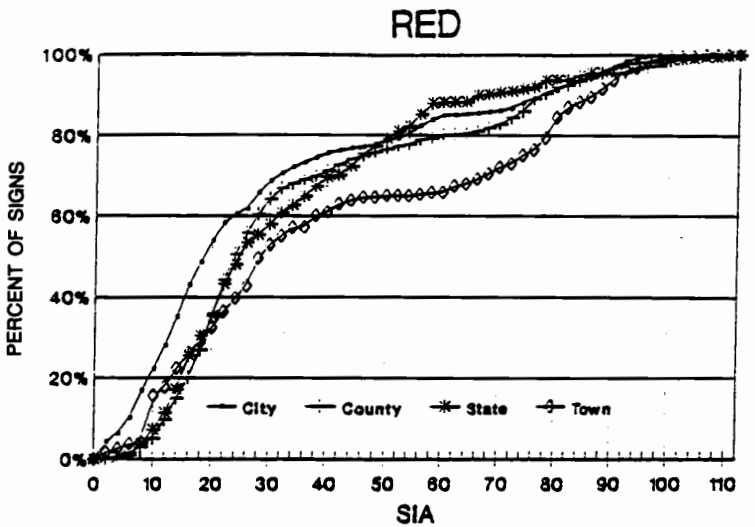


Figure 2. Frequency graph for red screened sheeting.

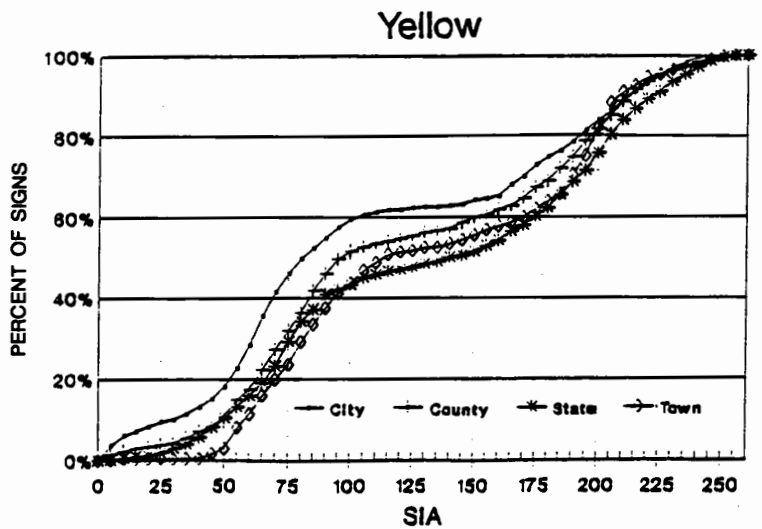


Figure 3. Frequency graph for yellow sheeting.

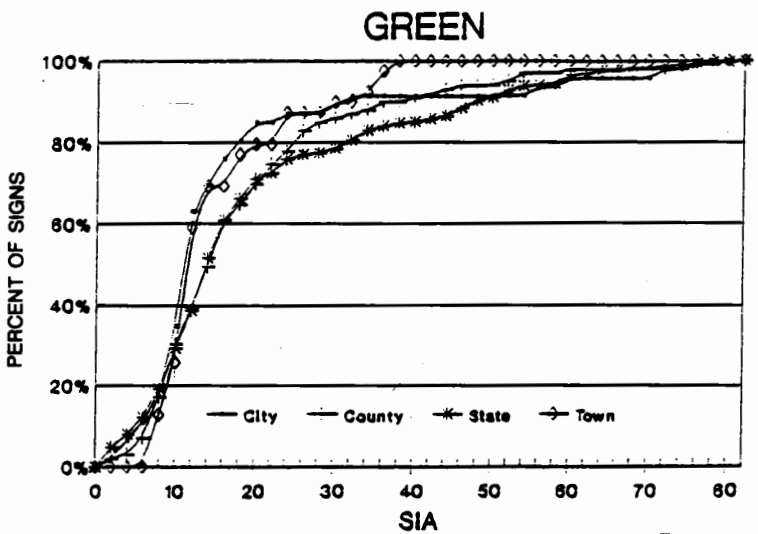


Figure 4. Frequency graph for green sheeting.

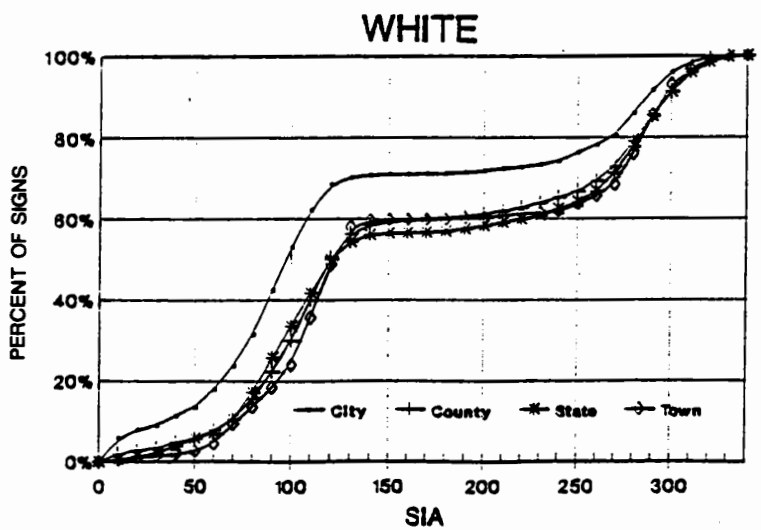


Figure 5. Frequency graph for white sheeting.

responded that 30 percent of their annual sign replacements were caused by poor retroreflectivity, while counties responded that only 16 percent of replacements were caused by this factor. Inadequate retroreflectivity was the leading cause of annual sign replacements according to the city responses. Vandalism was the leading cause of sign replacements in county jurisdictions. Nearly 40 percent of sign replacements in counties were caused by vandalism, while this factor accounted for 24 percent of the replacements in cities according to the survey responses.

The questionnaire survey also obtained sign density and sign population information for city and county agencies. Table 6 provides a summary of this information. City and county agencies have similar sign densities per capita. The cities responded as having approximately 114 total signs (not including street name and parking signs) per 1,000 persons, while counties were found to have approximately 122 total signs per 1,000 persons. The county agencies reported as having more warning and less guide signs than city agencies. Cities reported as having nearly three times the number of signs as counties on a per mile basis.

Several data files containing complete sign inventories from several small jurisdictions were obtained. Only one jurisdiction's (e.g., Kossuth County, Iowa) inventory included the date of sign installation. It is reasonable to assume that the date of installation closely reflects the age of the sheeting material. Table 7 provides the age distribution of signs from a small, rural jurisdiction. Nearly 30 percent of all signs had been installed for 5 years or more according to this database. As more jurisdictions implement a computerized sign inventory program that includes date of installation or replacement, the reliability of the distribution shown in Table 7 will be improved.

Table 4. Inventory types and data elements.

INVENTORY ITEM	PERCENT AND NUMBER OF JURISDICTIONS RESPONDING					
	CITY		COUNTY		State	
	%	N	%	N	%	N
Sign Inventory System	na	13	na	129	33	16
Inventory Type						
Main/Mini Computer	23	3	20	26	31	5
Micro Computer	38	5	32	41	50	8
Card/Paper	23	3	43	55	13	2
Other	16	2	5	7	6	1
Inventory Data Elements						
Sign Type	92	12	97	125	94	15
Installation Date	77	10	82	106	75	12
Replacement Date	77	10	83	107	75	12
Sheeting Type	54	7	50	64	56	9

na - not available

Table 5. Sign replacement and maintenance costs. Note in the table that county figures represent a weighted average value for rural and urban counties; sign fabrication and maintenance costs were not obtained from state agencies.

	CITY	COUNTY
Sign Fabrication Costs		
-Sign material cost per sign	$30	$38
-Labor cost per sign	$14	$19
-Equipment cost per sign	$10	$11
TOTAL cost per sign	$54	$68
Sign Maintenance Costs		
-Per mile costs	$135	$92
-Per capita costs	$1.20	$1.00
Reasons for Sign Replacement		
-Poor Retroreflectivity	30%	16%
-Knockdown	27%	23%
-Vandalism	24%	39%
-Other	19%	22%

Table 6. Sign population per capita and per roadway mile.

SIGN POPULATION PER CAPITA		
	CITY	COUNTY
Regulatory Signs per 1,000 persons	70	57
Warning Signs per 1,000 persons	38	63
Guide Signs per 1,000 persons	6	2
TOTAL	114	122
SIGN POPULATION PER ROADWAY MILE		
	CITY	COUNTY
Regulatory Signs per mile	18	4
Warning Signs per mile	10	4
Guide Signs per mile	1	3
TOTAL	29	11

Note: Street name and parking series signs not included.

Table 7. Age distribution of signs. (Source: Kossuth County, Iowa)

Age of Sign (years)	Number of Signs	Percent of Total Signs
12	202	4.1%
11	89	1.8%
10	165	3.3%
9	165	3.3%
8	236	4.8%
7	355	7.2%
6	260	5.3%
5	543	11.0%
4	1,561	31.6%
3	605	12.2%
2	497	10.0%
1	267	5.4%
Total	4,945	100%

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATION

This chapter presents the application of the findings presented in Chapter Two. The sign condition frequency graphs, sign density, and sign replacement cost information were compiled to test the economic consequences of establishing minimum retroreflectivity standards.

MINIMUM RETROREFLECTIVITY CRITERIA

In order to test the economic impacts of establishing retroreflectivity standards, actual minimum criteria needed to be identified. Selected preliminary results from the "Minimum Visibility Requirements for Traffic Control Devices" project sponsored by the Federal Highway Administration (FHWA) were obtained. These preliminary results include minimum retroreflectivity requirements for red, yellow, green, and white background signs. The minimum requirements are specified by sheeting color, roadway speed, sign placement, and sign size. Sheeting colors, roadway speeds, sign placements, and sign sizes other than those included here were evaluated in the "Minimum Visibility Requirements for Traffic Control Devices" project. The minimum SIA values tested here are preliminary and subject to change.

The following information provides a general discussion of the minimum retroreflectivity criteria provided by FHWA and selected for use in this project. Criteria for yellow sheeting signs were provided for right-mounted signs on 55-mile per hour (mph) roadways. This placement and roadway speed are appropriate for the majority of yellow warning signs. Two sign sizes—standard and standard plus 12 in.—were included. Minimum retroreflectivity values from 5 to 60 SIA for frequently used signs were recommended by FHWA. Minimum SIA criteria for red screened sheeting signs were provided for right-mounted signs on 30-mph and 55-mph roadways. The standard sign size was evaluated for the 30-mph condition and standard size plus 12 in. was assumed for the 55-mph application. The minimum standards for red sheeting ranged from 8 to 34 SIA. For green sheeting, minimum criteria were provided for freeway size signs on 65-mph roadways. Overhead and ground-mounted signs were both assumed in the minimum retroreflectivity standard. As the application of green sheeting material is limited, only a minimum standard of 10 SIA was provided. Finally, minimum SIA criteria were provided for right-mounted white sheeting signs on 10-, 30-, and 55-mph roadways. For white sheeting, sign size was limited to standard and standard plus 6 in. The range of minimum retroreflectivity values for frequently used white sheeting signs was from 10 to 100 SIA.

As ranges of SIA, instead of specific values, were provided from the FHWA research, it was appropriate to test multiple SIA values within each range. It was determined to test lower and upper SIA values within the ranges provided by FHWA for each sheeting color so that reasonable limits of the economic impact could be determined. Table 8 gives the values tested for each sheeting color. Several judgments were made to select the lower and upper SIA values for each sheeting color. The values selected for red sheeting represent the range of SIA which accommodates the driver needs for nearly all sign types and applications. For yellow sheeting, lower and upper values were selected from the FHWA recommendations. The lower standard (i.e., 20 SIA) was the reasonable limit to test because any values less than this would require little, if any, sign replacement. The upper value (i.e., 60 SIA) accommodates the driver needs for the large majority of sign types with yellow background. FHWA suggested that sign types requiring greater than 60 SIA were infrequently used or were poorly designed (i.e., unidentifiable symbol, unsatisfactory legend size, etc.). FHWA provided one value (i.e., 10 SIA) for green sheeting signs. This value was used as the upper limit because it exceeds the delivered specification of 9 SIA for new Type II sheeting provided in FP-85. A lower limit value of 8 SIA was selected in order to test a range of economic impacts. The lower value (i.e., 35 SIA) selected for testing white sheeting was not the absolute lowest SIA value provided by FHWA. However, minimum standards set at values below 35 SIA would not cause upgrades in current signing practices. The upper limit of 70 SIA for white sheeting was selected. FHWA suggested that white background signs where drivers require more than 70 SIAs are of generally poor design or they have letter sizes that are too small.

Table 8. Minimum SIA values selected for testing.

Sheeting Color	Minimum Retroreflectivity Values (SIA)	
	Lower Value	Upper Value
Red	8	21
Yellow	20	60
Green	8	10
White	35	70

The Florida DOT (*19*) reported end of service life SIA values for engineering grade sheeting as follows: yellow = 16 SIA, green = 5 SIA, and white = 40 SIA. These end of service life values are similar to the lower SIA values selected here for economic testing. Values for red, engineering grade sheeting were not available.

SIGNS REQUIRING REPLACEMENT

The percent of signs by sheeting color and jurisdiction type requiring replacement is provided in this section. The SIA fre-

quency graphs developed and presented in Chapter Two and the minimum retroreflectivity standards described previously in this chapter were used to estimate sign replacement. Table 9 specifies the percent of signs requiring replacement today by jurisdiction control for each selected minimum SIA criteria.

The replacement percentages for yellow sheeting signs range from 2 to 29 percent across all jurisdiction types assuming that the replacement occurred today. The state, county, and town replacement percentages were similar for the two minimum SIA criteria. Yellow sheeting signs on city roadways had considerably lower retroreflectivity levels than those of other roadways. The condition of red screened signs on city roadways is considerably worse than on other roadways. The overall condition, as reflected by the high replacement percentages (i.e., 3 to 57 percent), of red screened sheeting is poor. If the upper minimum SIA standard was applied, approximately 57 percent of red screened sheeting signs on city roadways would require replacement today. Even on the other jurisdiction roadways, at least 40 percent of red-screened sheeting signs would require replacement under the upper minimum SIA standard tested here.

The sign replacement percentages are also quite high for green sheeting. The results for the four jurisdiction types were consistent at the lower and upper minimum standards. Approximately 30 percent of green sheeting signs would require replacement today under the upper retroreflectivity standard tested here.

The sign replacement percentages for white sheeting are similar to those of yellow sheeting. The percentages range from 2 to 24 percent across the two minimum SIA standards for the four jurisdiction types. The sign replacement percentages for city roadways are considerably higher than those of the other three jurisdiction types. Approximately 24 percent of white sheeting signs would require replacement under the upper minimum standard tested here.

Table 9. Sign replacement by jurisdiction type.

Sheeting Color	Sign Type	Assumed Minimum SIA Standard	Percent of Signs Requiring Replacement by Jurisdiction Type Today			
			State	County	City	Town
Red	Regulatory	8 21	4% 40%	3% 40%	17% 57%	5% 34%
Yellow	Warning	20 60	2% 16%	3% 18%	9% 29%	1% 12%
Green	Guide	8 10	20% 30%	18% 31%	18% 35%	13% 26%
White	Regulatory	35 70	3% 11%	5% 11%	11% 24%	2% 10%

Table 10. Sign density per roadway mile.

	Signs per State roadway mile	Signs per county roadway mile	Signs per city roadway mile	Signs per town roadway mile
Red[1]	3	3	12	12
Yellow[2]	4	4	10	10
Green[3]	3	3	1	1
White[4]	1	1	6	6
TOTAL	11	11	29	29

Note: Sign densities were obtained from questionnaire survey for counties and cities. Sign densities for States were assumed to be similar to that of counties and towns were assumed to be similar to cities.

[1] Based on survey results for regulatory signs reported in Chapter 2 and factored by the ratio of red to white signs found from actual sign inventories for cities and counties.
[2] Based on survey results for warning signs reported in Chapter 2.
[3] Based on survey results for guide signs reported in Chapter 2.
[4] Based on survey results for regulatory signs reported in Chapter 2 and factored by the ratio of white to red signs found from actual sign inventories for cities and counties.

SIGN DENSITIES

Sign density information per roadway mile was obtained for this study and presented in Chapter Two. The density values were applied to the total roadway mileage resulting in estimates of total traffic signs. This calculation was completed for a national estimate and estimates for states, counties, cities, and towns. Table 10 provides the density estimates per mile for yellow, red, green, and white sheeting signs by jurisdiction type. The county and city sign densities were obtained from the questionnaire survey results presented in Chapter Two. The state sign densities were assumed to be similar to those of counties, and town sign densities were assumed to be similar to those of cities. The sign densities do not include parking series and street name signs.

SIGN REPLACEMENT COSTS

Replacement cost information for traffic signs was compiled. The replacement of traffic signs includes cost for the following items: sign and substrate materials, labor for manufacturing, labor for installation, equipment and travel, and maintenance of traffic.

A model to calculate replacement costs per sign was developed. This model is described by the following equation:

$$RC = SC + TC + (L \times R)$$

where: RC = average replacement cost, SC = sign cost including materials, fabrication, and labor for a mix of engineering grade and high performance sheeting signs, TC = transportation costs, L = labor hours for sign replacement and installation, and R = labor rate including direct rate, overhead, and fringe.

For the analysis, numerous cost and time assumptions were made. The key assumptions are detailed as follows:

1. *Sign Cost (SC)* — assumes average cost for materials, labor, and fabrication of standard-size ground-mounted traffic signs with the following sheeting material: engineering grade = $45.00 and high performance = $65.00.
2. *Transportation Cost (TC)* — assumes 10 miles of travel at $1.00 per mile per sign.
3. *Labor for Replacement (L)* — assumes one hour for two-person crew members or 2 man-hours for assembly and installation of a sign and the support, maintenance of traffic, and travel time. Assumes costs for traffic control devices are negligible and are available from other projects.
4. *Hourly Labor Rate (R)* — assumes $12.50 per hour direct labor rate plus 120 percent for overhead and fringe.

These cost and hour assumptions were applied to the cost model with the following results:

$$RC = \left(\frac{\$45 + \$65}{2}\right) + (10 \text{ miles} \times \$1.00/\text{mile}) + (2 \text{ man-hours} \times \$12.50/\text{hour} \times 2.20)$$

$$RC = \$120.00 \text{ per sign}$$

The sign replacement estimate of $120.00 per sign was used for all sheeting colors and sign types except for ground-mounted green signs. The increased size and time for installation for ground-mounted green guide signs doubled the replacement cost to $240 per sign. Any or all of these assumptions can be modified using location specific values. The differences in replacement costs between jurisdiction and area types were assumed to be negligible for the broad analysis completed here.

IMPLEMENTATION STRATEGIES

Four implementation strategies of the minimum retroreflectivity standards were identified for the economic analysis. The alternative strategies are described below:

Option 1—Immediate compliance with standards (base case). This option assumes complete compliance with all minimum retroreflectivity standards *within one year.* While this is not recommended and probably not feasible, the evaluation of this option provides the basis for comparison.

Option 2—Short-term compliance with standards. This option assumes complete compliance with all minimum retroreflectivity standards for all sign, roadway, and jurisdiction types *within 3 years.* It also assumes that jurisdictions would begin sign replacement activities immediately.

Option 3—Median-term compliance with standards. This option assumes complete compliance with all minimum retroreflectivity standards for all sign, roadway, and jurisdiction types *within 5 years.* It also assumes that jurisdictions would begin sign replacement activities immediately.

Option 4—Long-term compliance with standards. This option assumes complete compliance with all minimum retroreflectivity standards for all sign, roadway, and jurisdiction types *within 10 years.* This option could accommodate the use of currently stockpiled materials within the first several years of implementation.

Strategies other than the 3, 5, and 10 year even distribution schedules tested here could be applicable. The minimum standards could be phased in over 3 to 10 years by sign priority, starting with regulatory and critical warning signs. Also, sign upgrades could be completed by roadway classification over a specified time period starting with high type (i.e., freeways, expressways, arterials, etc.) facilities. Combinations of these strategies could be instituted. However, these other strategies identified here could not be readily evaluated for economic impacts. The algorithm for assessing these strategies would be quite complex and would not provide any significant increase in accuracy.

INSPECTION PROGRAM

In addition to the sign replacement costs the implementation of minimum retroreflectivity standards will require the initiation of a sign inspection program. Jurisdictions will require the means to identify traffic signs at or near the minimum retroreflectivity standards. Several methods are available for completing the field inspection of traffic signs including: visual nighttime inspection using trained personnel, Q-beam daytime inspection using trained personnel, portable retroreflectometer to measure SIA, and mobile retroreflectometer (Traffic Sign Evaluator (TSE)) developed by NCHRP (Project No. 5-10) and FHWA to measure SIA.



Figure 6. Operation of retroreflectometer.

The TSE provides for highway speed measurement of SIA values which should be an economical alternative for gathering retroreflectivity data as part of an inspection program. A prototype of the mobile TSE is currently being field tested at this time; therefore, it is not appropriate to consider this method for inspection here. A portable retroreflectometer can be used in the field to measure retroreflectivity. However, the instrument must be in contact with the sign face to take measurements. Figure 6 shows the field operation of a retroreflectometer. This method is time consuming when measuring a large quantity of signs.

Visual inspections conducted from moving vehicles during daytime or nighttime conditions are currently used throughout the country. A Washington State DOT study (*21*) showed that human observers can be adequately trained to perform visual inspections of traffic signs. Daytime visual inspections can be performed using a Q-beam light source. The Q-beam is used to flash a high intensity light onto a sign face and the human operator visually evaluates the retroreflective properties of the sheeting. Figure 7 shows the operation of a Q-beam light. This technique is used extensively by the Mississippi State Highway Department in its sign inspection program. With trained personnel the Q-beam inspection technique can be quickly completed. Nighttime visual inspections are performed by trained personnel using a vehicle's headlight beam to illuminate the traffic sign. The trained personnel visually evaluate the retroreflective properties of the illuminated sign face. This inspection technique can

be completed economically. However, because the technique is carried out at night issues of available staff, premium pay, and union regulations must be considered.

Costs per roadway mile to perform visual inspections were calculated for the daytime and nighttime techniques. The following tabulation provides the key assumptions and cost breakdowns for the two inspection techniques.

For daytime visual inspection with Q-beam lights, crew size = 2 persons; labor rate including overhead = $27.50 per hour; vehicle and equipment = $1 per mile; actual daily inspection time = 6 hours; and data collection rate = 25 miles per hour. Inspection costs for this inspection technique = $3.93 per roadway mile.

For nighttime visual inspection with vehicle headlights, crew size = 2 persons; labor rate = $27.50 per hour (includes overhead); premium pay for overtime = 50 percent; vehicle and equipment cost = $1 per mile; actual daily inspection time = 6 hours; and data collection rate = 25 miles per hour. Inspection costs for this inspection technique = $5.40 per roadway mile.

The inspection costs presented here are rough estimates only. The subsequent analysis assumes $5.00 per mile for inspection costs. A sign inspection program will be necessary to ensure adequate compliance with the proposed minimum retroreflectivity standards.

SIGN INVENTORY PROGRAM

The application of a sign inventory system will assist agencies in maintaining the retroreflectivity of traffic signs above the established minimum criteria. The intent of the sign inventory is to track sheeting deterioration through date of installation or actual in-service SIA readings of individual signs. Tracking sheeting deterioration is critical to ensuring compliance with minimum retroreflectivity standards. Beyond the simple sign inventory database, FHWA is currently finalizing models for predicting required and available retroreflectivity. These models will be incorporated into the Sign Management System (SMS). The predictive models will use information from the sign inventory to identify when signs need to be inspected or replaced for reasons of insufficient retroreflectivity.

Considerable cost can be incurred in establishing a sign inventory system. Initial costs include the inventory of existing traffic signs within the jurisdiction. Once the signs have been initially logged the maintenance of the inventory can be accomplished through the work-order process, thus adding only minor costs. Several techniques for inventorying signs are available including manual, photolog, and videolog methods. Table 11 summarizes the data collection cost ranges for manual, photolog, and videolog inventories for cities and counties and for urban and rural areas in Minnesota.

Other methods of tracking sheeting deterioration can be established by an agency. Sign dating programs have been established in small and large jurisdictions. An effective sign dating program includes the following elements: a color-coded sticker with date of installation affixed to each sign panel; a portable retroreflectometer to periodically measure SIA from test samples and selected inservice signs; and a replacement program based on sign age, climatological, and other variables identified from test rack samples.



Figure 7. Operation of Q-Beam.

Table 11. Sign inventory data collection costs. (Source: Refs. 21, 22)

Agency	Range of Cost For Manual Data Collection		
City	$15-$27/mile		
County	$10-$15/mile		
	Range of Cost Per Inventory Method		
Area Type	Manual	Photolog	Videolog
Urban	$80-135/mile	$45-$70/mile	$30-$70/mile
Rural	$15-$45/mile	$25-$30/mile	$15-$25/mile

This method would rely on test samples and general deterioration characteristics. Sign replacement needs of deficient signs would be identified by using the color-coded sticker system.

ECONOMIC ANALYSIS METHODOLOGY AND RESULTS

This section presents the methodology and results of the economic impact analysis of the proposed minimum in-service retroreflectivity standards. To complete the analysis the following general items must be determined: (1) total signs requiring replacement, (2) cost to replace signs, and (3) implementation schedule of the minimum standards. Within each of the basic components numerous other information and data are required. Figure 8 provides a flow diagram of the assessment methodology. Although this methodology was developed specifically for this research, it is believed that the methodology could be applied to most other jurisdictions. The data needs and procedures associated with the process are presented as follows:

1. Using SIA data collected throughout the country, establish frequency graphs of sign sheeting condition.
2. Select minimum retroreflectivity standards to test.
3. Apply minimum standards to frequency graphs to determine percent of signs requiring replacement by sheeting color and by jurisdiction type.
4. Remove deficient signs from database.
5. Replace deficient signs with new signs using equal mix of engineering-grade, super-engineering-grade, and high-perform-

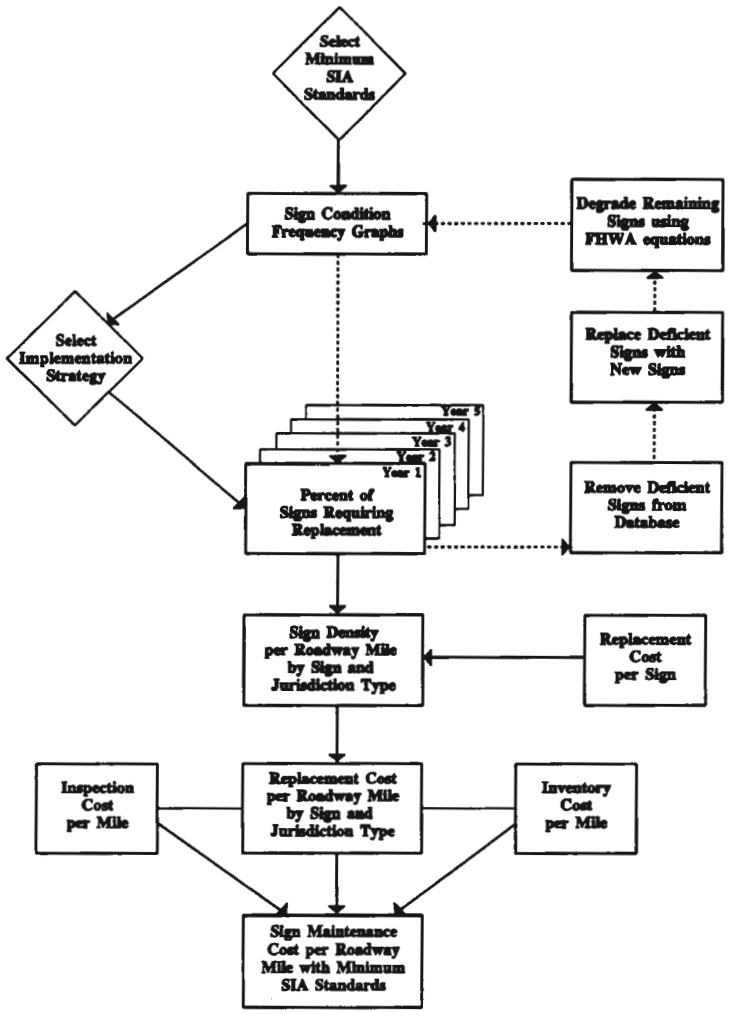


Figure 8. Process for economic assessment.

ance-grade sheeting material to represent the change in market share towards brighter materials.

6. Assign SIA values for new signs using the regression equations developed for FHWA's "Service Life of Retroreflective Traffic Signs" project for engineering-grade and high-performance-grade sheeting. Assign SIA values for super-engineering-grade sheeting material based on measurements taken on test rack samples by FHWA.

7. For non-new sheeting material in the database, reduce the SIA values using the regression equations from FHWA's "Service Life of Retroreflective Traffic Signs" report.

8. Prepare new sign condition frequency graphs for the revised database.

9. Use the minimum SIA standards to determine percent of signs requiring replacement.

10. Repeat steps 4 to 9 until implementation schedules are satisfied.

11. Use sign density data to determine the number of signs per roadway mile requiring replacement by sheeting color and jurisdiction type.

12. Use sign replacement cost data to determine the cost per roadway mile for each year of the implementation schedule and for annual maintenance thereafter.

13. Determine per mile costs for annual sign inspection by manual methods.

14. Determine per mile costs for the establishment of a sign inventory system. The development of the inventory system would coincide with the minimum standards implementation schedules.

15. Combine projected replacement, inspection, and inventory costs and compare to existing sign maintenance budgets to evaluate the economic impacts of the minimum standards.

These procedures and processes were used to complete the evaluation. The minimum SIA standards were not assumed to apply to parking series, street name and overhead guide signs. The model was run for 1-, 3-, 5-, and 10-year implementation schedules with the assumption that jurisdictions would commence upgrading their signs from the inception of the standards. The implementation schedules of 3, 5 and 10 years assumed an

even distribution of replacement and inventory costs. Annual maintenance costs beyond each implementation schedule were also estimated.

For comparative purposes average annual sign maintenance budgets per roadway mile are also presented. While the economic analysis results here can be tested for reasonableness versus current sign maintenance budgets, the analysis procedures were not developed to determine costs to individual jurisdictions.

The actual or estimated sign maintenance budgets were obtained from the survey responses reported in Chapter Two. The annual maintenance budgets include sign replacement, inspections, inventory, and other related activities. Each annual sign budget was divided by the total jurisdiction controlled roadway mileage to obtain the estimated annual sign maintenance cost per roadway mile. Table 12 summarizes these costs. The high sign densities in urban areas are reflected in their per mile costs.

To test the incremental costs associated with the implementation of minimum standards, predicted sign maintenance costs per roadway mile were needed. The maintenance costs would include sign replacements, establishment of sign inventory, and sign inspection programs on a per mile basis. The costs for inventories and inspections were obtained from information received from agencies and previously presented in this chapter.

Sign replacement costs for state, county, city, and town-controlled roadways were developed for red, yellow, green, and white sheeting on the minimum SIA criteria previously presented. Each sheeting color was tested using the lower and upper minimum SIA standards. As stated previously, the economic assessment was completed for 1-, 3-, 5-, and 10-year implementation schedules. The economic model was run for a total of 11 years to obtain the annual maintenance costs for the years after the minimum standards have been implemented.

Sign replacement costs in terms of dollars per roadway mile for state, county, city, and town-controlled roadways were developed. These are presented in Appendix D. Similar to state roadways, the majority of sign replacement budgets in counties, cities, and towns would be designated for replacement of green and red sheeting signs. There is a considerable difference in replacement costs between the lower and upper standards, especially for the red, green, and white sheeting. The replacement cost for green sheeting represents 65 to 75 percent of the total replacement cost. Several reasons for this are apparent:

1. Average cost per sign to replace green guide signs is nearly twice that of standard warning and regulatory signs due to sign size.
2. Majority of green guide signs are constructed using engineering-grade sheeting, which has lower retroreflectivity characteristics than the other sheeting types.
3. Minimum retroreflectivity standards for green sheeting tested here were high and in the case of the upper value (i.e., 10 SIA) higher than the delivered new specification for green, engineering grade sheeting listed in FP-85.
4. Many of the green sheeting samples collected across the country had SIA values less than 8 SIA, which was the lower standard tested here.

On all roadways the need for replacement of red sheeting signs was quite high. The problems of color fade of this sheeting type contribute to the overall poor condition of these signs. In several instances the annual maintenance costs actually increased after the implementation schedule was completed. The population of signs for this evaluation was deteriorated, using the equations and relationships developed in FHWA's "Service Life of Retroreflective Traffic Signs" project. High annual costs after the standards implementation are the product of a large population of signs of similar age (i.e., 5 or more years old) failing to meet the minimum criteria in the years after the schedule has been fulfilled.

Table 12. Annual sign maintenance cost.

Jurisdiction Type	Annual Maintenance Cost
County - Urban	$120/mile
County - Rural	$ 80/mile
City	$135/mile

The predicted sign maintenance costs per mile per year are presented in Tables 13, 14, 15, and 16. Each table includes the costs associated with lower and upper SIA. The shaded areas highlight the annual maintenance cost (in dollars per mile) for each year of the specified implementation schedule. The unshaded areas show the annual cost per mile to maintain the minimum standards after implementation is completed. Once the programs have been established either after 1, 3, 5, or 10 years, a steady-state condition of maintenance cost occurs.

Table 17 summarizes the replacement, inspection, and inventory costs for a typical year of the implementation schedule for the 1-, 3-, 5-, and 10-year alternatives. For clarification, if the 3-year minimum standard schedule was selected, the initiation of a sign inventory would be allocated evenly across the 3-year time period. The cost for maintaining a sign inventory was neglected because it is rather minimal as compared to the other sign maintenance costs on a per mile basis.

Table 18 provides a comparison of the average sign maintenance costs per mile. The comparison is between the projected costs with the minimum standards and the current costs reported by jurisdictions. The increased cost due to the implementation of minimum retroreflectivity standards is represented by the difference between the projected and existing maintenance costs.

Projected sign costs per mile were combined using the ratios of state, county, city, and town mileage as compared to total national mileage as supplied by the Highway Performance Monitoring System (HPMS) (*25*). The difference or increment between the projected and existing per mile costs is summarized in Table 19.

Table 19 shows the estimated national economic impact in terms of yearly incremental maintenance costs of a sign retroreflectivity standard implemented over four different time periods. To arrive at these estimates, shown in the last column, the following calculations were made:

1. The projected per mile maintenance costs, shown in the second column, is a composite cost for each of the four jurisdiction types derived by obtaining an average of the sign maintenance costs given in Table 18, weighted by their respective highway mileage.
2. The existing per mile maintenance costs of $100 was selected as a composite average value on the results of questionnaire survey responses from 155 jurisdictions.

Table 13. Sign maintenance costs for state roadways.

	STATE ROADWAYS - dollars per mile per year							
	LOWER SIA STANDARDS				UPPER SIA STANDARDS			
	Implementation Schedule				Implementation Schedule			
Year	1 yr	3 yr	5 yr	10 yr	1 yr	3 yr	5 yr	10 yr
1	223	104	82	80	596	260	195	139
2	38	104	82	80	66	260	195	139
3	54	104	82	80	123	260	195	139
4	36	36	82	80	80	80	195	139
5	63	63	82	80	111	111	195	139
6	73	73	73	80	76	76	76	139
7	68	68	68	80	89	89	89	139
8	80	80	80	80	79	79	79	139
9	79	79	79	80	99	99	99	139
10	70	70	70	80	73	73	73	139
11	85	85	85	85	145	145	145	145

Table 14. Sign maintenance costs for county roadways.

	COUNTY ROADWAYS - dollars per mile per year							
	LOWER SIA STANDARDS				UPPER SIA STANDARDS			
	Implementation Schedule				Implementation Schedule			
Year	1 yr	3 yr	5 yr	10 yr	1 yr	3 yr	5 yr	10 yr
1	231	111	85	76	635	273	197	139
2	52	111	85	76	74	273	197	139
3	50	111	85	76	112	273	197	139
4	45	45	85	76	86	86	197	139
5	51	51	85	76	78	78	197	139
6	46	46	46	76	72	72	72	139
7	80	80	80	76	97	97	97	139
8	46	46	46	76	59	59	59	139
9	88	88	88	76	117	117	117	139
10	69	69	69	76	56	56	56	139
11	75	75	75	75	144	144	144	144

Table 15. Sign maintenance costs for city roadways.

	CITY ROADWAYS - dollars per mile per year							
	LOWER SIA STANDARDS				UPPER SIA STANDARDS			
	Implementation Schedule				Implementation Schedule			
Year	1 yr	3 yr	5 yr	10 yr	1 yr	3 yr	5 yr	10 yr
1	307	152	130	101	828	371	254	159
2	98	152	130	101	96	371	254	159
3	54	152	130	101	193	371	254	159
4	90	90	130	101	57	57	254	159
5	99	99	130	101	96	96	254	159
6	117	117	117	101	39	39	39	159
7	50	50	50	101	72	72	72	159
8	74	74	74	101	50	50	50	159
9	45	45	45	101	96	96	96	159
10	62	62	62	101	53	53	53	159
11	85	85	85	85	164	164	164	164

Table 16. Sign maintenance costs for town roadways.

	TOWN ROADWAYS - dollars per mile per year							
	LOWER SIA STANDARDS				UPPER SIA STANDARDS			
	Implementation Schedule				Implementation Schedule			
Year	1 yr	3 yr	5 yr	10 yr	1 yr	3 yr	5 yr	10 yr
1	202	99	99	81	582	288	206	137
2	63	99	99	81	127	288	206	137
3	32	99	99	81	153	288	206	137
4	71	71	99	81	63	63	206	137
5	128	128	99	81	105	105	206	137
6	78	78	78	81	73	73	73	137
7	68	68	68	81	55	55	55	137
8	45	45	45	81	68	68	68	137
9	78	78	78	81	62	62	62	137
10	35	35	35	81	83	83	83	137
11	79	79	79	79	170	170	170	170

Table 17. Sign maintenance costs per roadway mile.

Implementation Schedules	Annual Replacement Cost of Deficient Sheeting per mile				Annual Sign Inventory Cost per mile[1]	Annual Sign Inspection Cost per mile
	State	County	City	Town		
1 YEAR (BASE CASE)						
-lower standard	$193	$201	$277	$172	$ 25	$5
-upper standard	$491	$530	$723	$477	$100	$5
3 YEAR PROGRAM						
-lower standard	$ 91	$ 98	$139	$ 86	$ 8	$5
-upper standard	$222	$235	$333	$250	$ 33	$5
5 YEAR PROGRAM						
-lower standard	$ 72	$ 75	$120	$ 89	$ 5	$5
-upper standard	$170	$172	$229	$181	$ 20	$5
10 YEAR PROGRAM						
-lower standard	$ 72	$ 68	$ 93	$ 73	$ 3	$5
-upper standard	$124	$124	$144	$122	$ 10	$5

[1]Represents low and high range values for the specified maintenance activity. The difference in cost between the low and high values is not attributable to the lower and upper SIA standards, but reflects differences in reported and computed per mile costs.

3. The incremental increase in maintenance costs shown in the third column is simply column 2 minus column 3, with any resulting negative values limited to $0.

4. The total yearly incremental maintenance cost shown in the last column was obtained by multiplying the per mile incremental cost by the national roadway mileage of 3.8 million.

The results indicate that there would be a substantial economic impact if the standard were to be implemented within a 1-year period. The incremental cost decreases significantly as the implementation period is increased. For a 5-year or longer implementation period there would be no increase in sign maintenance cost for the lower standards. In fact, a net reduction in annual maintenance cost could be experienced. This would result from the replacement of older, engineering-grade signs with new super-engineering and high-performance sheeting which have a higher level of retroreflectivity for a longer period. Approximately 60 percent of the signs sampled for this project were constructed with engineering-grade sheeting.

The sign replacement algorithm used to evaluate economic impacts replaced deficient signs with an equal mix of engineering-grade, super-engineering-grade, and high-performance-sheeting signs. The replacement scenario vastly improves the retroreflectivity levels and effective life of the population of signs. Therefore, under certain implementation time schedules and minimum standards, a reduction in replacement costs could be realized. If the mix of sheeting remains unchanged from existing conditions, substantially higher costs than those represented here for sign replacements would be expected.

These estimates, which are presented in current (1990) dollars, are based on previously explained assumptions concerning replacement of signs using different retroreflective sheeting types, and on jurisdiction reported values for average per mile maintenance costs and sign densities. The assumptions and values used in this analysis are reasonable and sufficiently accurate to provide these order of magnitude costs. Given the methodology presented in this report, each jurisdiction can use its own cost values and sign densities to determine its specific economic impacts.

Table 18. Existing and projected sign maintenance costs.

Area Type	Existing reported sign costs per mile			
Urban	$135			
Rural	$ 80			
Implementation Schedule	Projected sign costs per mile with standards			
	State	County	City	Town
1 year program				
- lower standard	$223	$231	$307	$202
- upper standard	$596	$635	$828	$582
3 year program				
- lower standard	$104	$111	$152	$ 99
- upper standard	$260	$273	$371	$288
5 year program				
- lower standard	$ 82	$ 85	$130	$ 99
- upper standard	$195	$197	$254	$206
10 year program				
- lower standard	$ 80	$ 76	$101	$ 81
- upper standard	$139	$139	$159	$137

Table 19. National impact of retroreflectivity standards on sign maintenance costs.

Implementation Schedule	Projected per mile maintenance costs[1]	Existing reported per mile maintenance costs[2]	Incremental increase in maintenance costs per mile[3]	Total yearly incremental maintenance costs in millions[4]
1 year program				
- lower standard	$235	$100	$135	$513
- upper standard	$644	$100	$544	$2,067
3 year program				
- lower standard	$113	$100	$ 13	$ 49
- upper standard	$286	$100	$186	$707
5 year program				
- lower standard	$ 93	$100	$ 0	$ 0
- upper standard	$207	$100	$107	$407
10 year program				
- lower standard	$ 82	$100	$ 0	$ 0
- upper standard	$141	$100	$ 41	$156

[1] Weighted average of State, county, city, and town costs per mile.
[2] Estimate of existing maintenance costs for urban and rural areas.
[3] Difference between projected and existing maintenance costs
[4] Result of per mile maintenance costs and total national highway mileage

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The objectives of this project were to determine (1) the overall retroreflective condition of the nation's traffic signs, (2) determine sign replacement and maintenance costs, (3) estimate the number of deficient traffic signs in the field today, and (4) evaluate the economic consequences of establishing minimum retroreflectivity standards.

The condition of signs was found to vary by sheeting color, sheeting type, and jurisdiction type. Traffic signs on city roadways were in considerably poorer condition than the other jurisdiction's signs. The population of red and green signs was found to have low retroreflectivity values as compared to the minimum standards tested.

State, county, and city agencies provided sign maintenance and replacement costs. The materials, labor, travel, and equipment costs to replace a warning or regulatory sign of standard size was determined to be approximately $120. A ground-mounted guide sign costs approximately $240 to replace based on the best available information. Agencies reported that annual sign maintenance budgets require between $80 and $135 per roadway mile. Because of sign density urban areas incur higher per mile costs than do suburban and rural areas.

Once minimum standards are established agencies will need to consider implementing sign inventory and inspection programs to ensure compliance. Sign inspections conducted visually by trained personnel either during the day or at night can be adequately accomplished at costs accounting for less than 5 percent of maintenance budgets. The establishment of a sign inventory requires significant funding to initially log all signs. Once the data collection is complete the upkeep of the system can normally be accomplished through daily maintenance activities and work order processes. Sign inventories and inspection programs would be essential to maintaining signs above minimum standards.

Two levels of minimum retroreflectivity standards and three alternative implementation schedules were tested in this research. The projected annual sign maintenance costs per mile at the lower standards for the 3-, 5-, and 10-year implementation schedules were in the same range as existing sign maintenance costs and, thus, should have relatively minor economic impacts on jurisdictions. This finding suggests that current sign maintenance standards are adequately maintaining signs above the lower standards tested here. It should be emphasized however, that these conclusions derive from random national samples of existing sign retroreflectivity. Therefore, depending on any specific jurisdiction's current standards, the standards tested here could result in costs for sign replacement due to insufficient retroreflectivity that vary somewhat from the average costs reported here.

The economic impact of the higher retroreflectivity standards was found to be considerable. The annual costs for replacement, inventory, and inspection could be as much as 2 to 6 times that of current budgets. In some instances as many as 60 percent of all signs of a particular sheeting color could require replacement within city jurisdictions. The research here seems to have identified the reasonable economic impact boundaries through the testing of two sets of minimum standards.

The algorithm applied to estimate sign replacement costs assumed a shift towards the use of brighter and longer lasting sheeting material. The use of the brighter material could over time reduce the annual sign maintenance costs as reflected in Table 19 under the 5- and 10-year implementation schedules and with the lower SIA standards.

SUGGESTED RESEARCH

Through this project several other research requirements became apparent, as outlined in the following:

1. Preferred techniques for sign inspection should be identified. Detailed cost assessments for preferred inspection techniques should be completed.
2. When the Traffic Sign Evaluator (TSE) is available an economic assessment of sign inspection cost should be conducted.
3. The effects of color fade on red sheeting should be evaluated. A minimum SIA standard for red sheeting does not seem appropriate, as SIA can actually increase over time.
4. Once minimum SIA standards are selected research on specific implementation plans and schedules should be conducted. The implementation strategies must be simple and uniform in their application. This research should include identification of funding sources.
5. Research on liability costs from accidents involving inadequate signing should be included in future economic analysis.

APPENDIX A—LITERATURE REVIEW

The following three topic areas were focused on during the review of literature:

1) Principles of retroreflection and retroreflective sheeting materials.

2) Specifications for retroreflective sheeting materials.

3) Sign luminance requirements, feasibility of performance standards and sign maintenance practices.

PRINCIPALS OF RETROREFLECTION

Nearly all signs have to be legible and color distinguishable at night as well as day. While this can be accomplished through external illumination of the signs, retroreflection is the most commonly used means of making signs visible to the driver at night. Three reports, "Retroreflectivity of Roadway Signs for Adequate Visibility: A Guide" (4),"Maintenance Management of Street and Highway Signs" (5) and "Guide to the Properties and Uses of Retroreflectors at Night" (6) are the primary sources of the background information.

Retroreflection occurs when light rays strike a surface and are redirected back to the source of light. Two principles followed to achieve retroreflectivity for roadway signs are prismatic and spherical lens retroreflection. Prismatic, also known as cube-corner, retroreflection is achieved through total internal reflection. As shown in the top illustration of Figure A-1, incoming light hits the first surface and reflects to the rear surface which reflects it to the last surface which reflects the light rays back to the source. Typically, the prismatic device reflects light off these surfaces at 90 degrees to each other, i.e. the corner of the cube. In the second type, spherical lens retroreflection is achieved through a combination of a glass sphere (bead) and a reflecting (mirror type) surface placed at the focal point. As shown in the bottom illustration of Figure A-1 an incoming ray is bent and

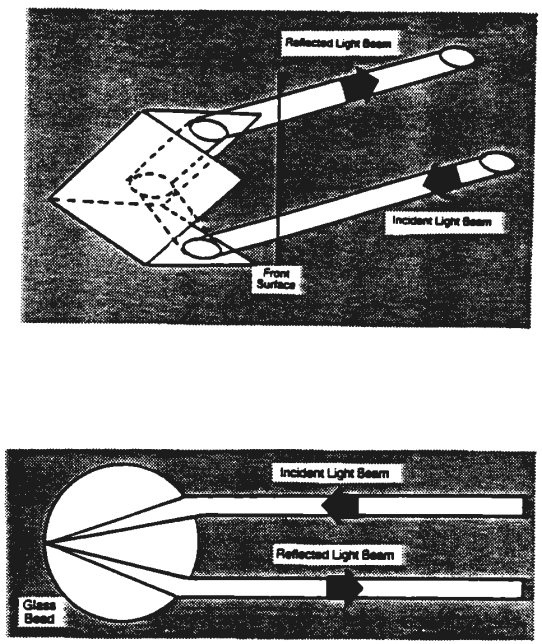


Figure A-1. Two types of retroreflection, cube-corner (top) and spherical lens (bottom).

directed inside and toward the back of the sphere, reflecting off the reflective surface, and after being bent at the exterior of the sphere redirected toward the light source.

TYPES OF RETROREFLECTIVE SHEETING

Retroreflective sheeting consists of micro cube-corners or spheres enclosed in a weather resistant transparent plastic film. To reflect color, pigment or dye is inserted into the film or on the reflecting surface. Figure A-2 shows a typical construction of cube-corner retroreflective sheeting. This type of sheeting is typically manufactured with an air cushion behind the cubes. A unique property of this sheeting is its high coefficient of retroreflection at low entrance angle, which means it appears bright at long distances if the device is not too far laterally removed from the light source.

There are three types of spherical lens (bead) retroreflective sheeting -- 1) exposed glass bead, 2) enclosed glass bead, and 3) encapsulated glass bead. These are shown in Figure A-3.

In the exposed lens sheeting the front half of the glass beads are exposed to the outside air. Glass beads work best when exposed to the air. However, because of the small size of the beads, a film of water can cover the beads when it rains and can greatly reduce the retroreflectivity of the beads. Hence, this type of sheeting is not recommended for traffic signs and generally is not included in State or federal specifications. Nonetheless, exposed lens sheeting is still found on traffic signs on some low-volume rural roads controlled by local jurisdictions.

Enclosed lens sheeting material consists of a layer of transparent plastic of appropriate color in which glass beads are imbedded. A metallic reflection shield is provided behind the plastic, with a layer of adhesive and with a protective liner that is removed during sign fabrication. The plastic covering enables the sheeting to be equally bright under dry and wet

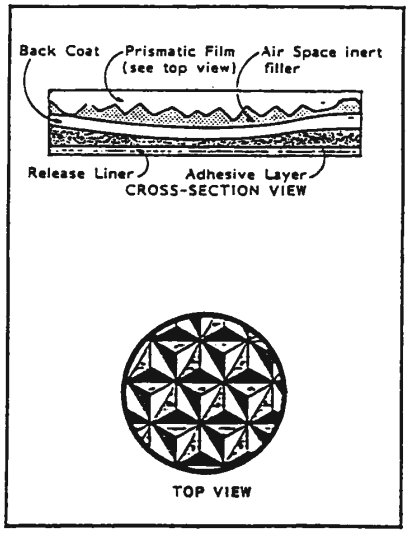


Figure A-2. Cross-section and top view of cube-corner retroreflective sheeting.

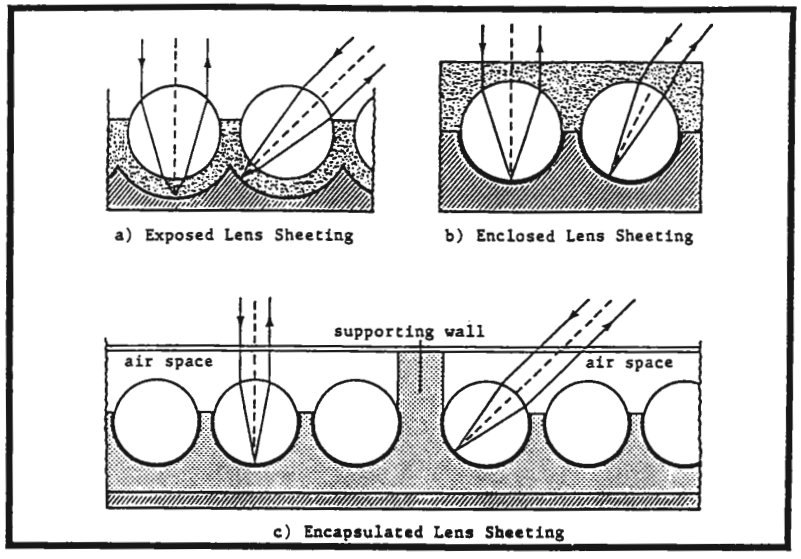


Figure A-3. Cross-section view of three types of spherical lens retroreflective sheeting.

weather conditions.

With encapsulated lens sheeting the glass beads are also protected by a transparent material that is supported slightly above the beads by walls creating an air filled compartment. The back of the beads are covered with a reflective surface. The resulting airspace in front of the beads makes it more reflective and, hence, is known as high performance sheeting.

PROPERTIES OF RETROREFLECTIVE SHEETING

One of the most important properties of retroreflective sheeting is the ability to return light which is commonly described by a variety of terms including brightness, retroreflectance, luminance or candlepower. The International Commission of Illumination (CIE) (6) uses the term coefficient of luminous intensity, which is defined as the ratio of luminous intensity of reflector in the direction of the observation to the illumination at the retroreflector on a plane perpendicular to the light. In the International System of Units (SI), i.e. the metric system, it is expressed as candelas (cd) per lux (lx). It is a measure of efficiency of the retroreflector because it describes the amount of luminance (candelas) that comes out from the retroreflector per amount of light (lux) coming in from the light source, i.e., the vehicle headlights. This definition treats the retroreflector as a point source. But because signs have a relatively large area, they are treated as an extended light source which may be thought of as consisting of many point sources each with a luminance intensity of one candela. To account for this the term coefficient (R_A) of retroreflection has been adopted by the CIE. It is merely the coefficient of luminous intensity divided by the area and expressed in SI units as candelas per lux per square meter. The English equivalency is candelas per footcandle per square foot and in the *FP-85* (7) is described as specific intensity per unit area (SIA). The conversion from English to metric (SI) is unity; hence, a value expressed in SIA terms is the

same value in R_A terms.

The retroreflectance of sheeting materials is described in context of another important property, its angularity, which is defined by the entrance (of the light) and the observation (of the motorist) angles. The entrance angle is the angle formed between a light beam striking the surface of a sign and a line coming out perpendicular from the surface. The entrance angle changes with distance between the vehicle and is a function of the location of the sign and the vehicle. An entrance angle of 30 degrees is considered wide for highway signing. The observation angle is the angle between the incoming light beam and the reflected light beam and is a function of the height of the drivers eye with respect to the vehicle headlamps. Figure A-4 illustrates the entrance and observation angles.

Since a retroreflective material is supposed to reflect most of the light directly back to the source, the optimum observation angle should be zero. However, in reality this is not the case since the driver's eye is higher than the vehicle headlight and can range from 21 inches for small cars to as much as 64 inches for large trucks. A wide observation angle is anything over 2 degrees. For purchase specifications, minimum SIA is prescribed for each type of sheeting for two observation angles, two entrance angles, and the different colors.

SPECIFICATIONS FOR RETROREFLECTIVE SHEETING

There are at least four "national" specifications for reflective sheeting:

1. Federal Specification L-S-300C, a General Services Administration specification.
2. Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (*FP-85*).
3. AASHTO M268 - Retroreflective Sheeting for Traffic Control by the

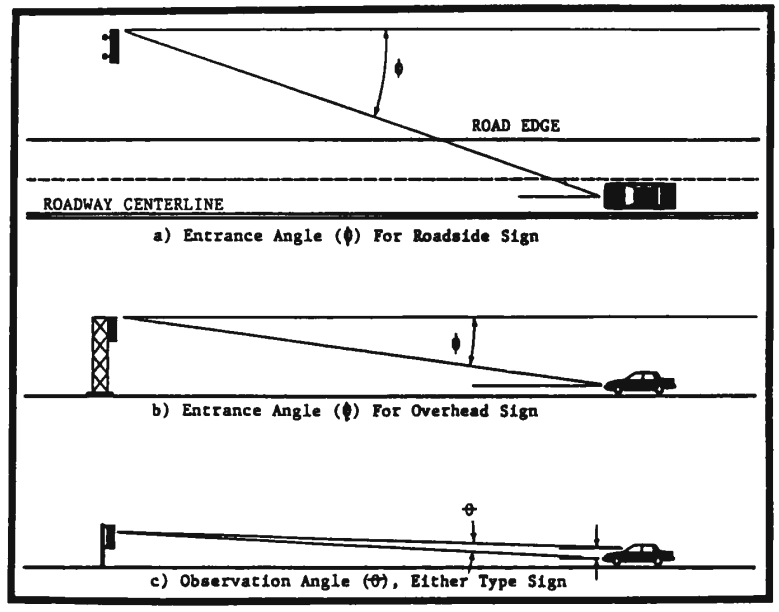


Figure A-4. Entrance and observation angles.

American Association of State Highway Officials.

4. ASTM D 4956, Reflective Sheeting Standards by the American Society for Testing Materials.

The following specifications, related to retroreflectance, were a primary source of information:

1. *FP-85*, Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects.
2. Federal Test Method Standard 370, Instrumental Photometric Measurements of Retroreflective Materials and Retroreflective Devices.
3. The following ASTM standards on color and appearance measurement
   - E808-81,"Standard Practice for Describing Retroreflection"
   - E809-81,"Standard Practice for Measuring Photometric Characteristics of Retroreflectors"
   - E810-81,"Standard Test Method for Coefficient of Retroreflection of Retroreflective Sheeting"
   - E811-81,"Standard Practice for Measuring Colormetric Characteristics of Retroreflectors Under Nighttime Conditions"

In the *FP-85* three types of retroreflective sheeting are recognized. The first type has two classes: Type II and Type II A, commonly called engineering and super engineering grade sheeting, respectively. They are both enclosed lens type sheeting with the main distinction between the two being a higher quality glass bead in Type II A. Table A-1 shows the minimum SIA values for Type II and Type II A sheeting. As shown in Table A-1 the minimum SIA values for Type II A specified by *FP-85* are about twice those for Type II.

Table A-1 Specific Intensity Per Unit Area (SIA) for Type II sheeting.

Type II Sheeting

Observation Angle (o)	Entrance Angle (o)	White	Red	Orange	Brown	Yellow	Green	Blue
0.2	-4	70	14.5	25.0	2.0	50	9.0	4.0
0.2	+30	30	6.0	7.0	1.0	22	3.5	1.7
0.5	-4	30	7.5	13.5	1.0	25	4.5	2.0
0.5	+30	15	3.0	4.0	0.5	13	2.2	0.8

Type II-A Sheeting

Observation Angle (o)	Entrance Angle (o)	White	Red	Orange	Brown	Yellow	Green	Blue
0.2	-4	140	30	60	5	100	30	10
0.2	+30	60	12	22	2	36	10	4
0.5	-4	50	10	20	2	33	9	3
0.5	+30	20	6	12	1	20	6	2

Table A-2 Specific Intensity Per Unit Area (SIA) for Types IIIA, B and C.

A - Glass Bead Retroreflective Element Material

Observation Angle (o)	Entrance Angle (o)	White	Red	Orange	Yellow	Green	Blue
0.2	-4	250	45	100	170	45	20.0
0.2	+30	150	25	60	100	25	11.0
0.5	-4	95	15	30	62	15	7.5
0.5	+30	65	10	25	45	10	5.0

B and C - Prismatic Retroreflective Element Material

Observation Angle (o)	Entrance Angle (o)	White	Red	Orange	Yellow	Green	Blue
0.2	-4	250	45.0	100	170	45.0	20.0
0.2	+30	95	13.3	26	64	11.4	7.6
0.5	-4	200	28.0	56	136	24.0	18.0
0.5	+30	65	10.0	25	20	10.0	5.0

The next type has three classes: Type III A and III B, which are in *FP-85*, and Type III C, which was added to *FP-85* by an FHWA memorandum dated November 3, 1989. Two classes are encapsulated type sheeting with Type III A made of glass beads and Types III B and III C made of prismatic reflectors. All types provide much higher brightness than both Type II and Type II A. Their respective minimum reflectance values are shown in Table A-2.

In the *FP-85* there is reference to a "Type III Reboundable" sheeting. This is a retroreflective material intended to be applied to flexible impact resistant plastic devices such as plastic drums used as channelizing devices in work zone traffic control. It is referred to as "reboundable" because it can withstand expansion and contraction and will not crack easily when hit by a vehicle or roughly handled as is the case for standard Type III A sheeting used on permanent signs.

The last type of sheeting recognized in the *FP-85* is labeled as Type IV. This type is a high performance vinyl sheeting of low durability that is used for retroreflective white collars around orange cones, and for fold-up temporary signs of the kind commonly used by utility companies. The primary distinction between the sheeting types is their brightness, as noted in the minimum SIA specifications, and durability.

The typology presented in *FP-85* is simply a method for grouping products available when the specification was made. Other organizations, notably the American Society for Testing Materials (ASTM) and American Association of State Highway and Transportation Officials (AASHTO), and the General Services Administration (GSA) have different typologies and SIA specifications. Table A-3 compares the typologies for the four most common specifications mentioned previously. Table A-4 compares the SIA specifications from the four agencies for their different types the 0.2° angle and the -4° entrance angle. Table A-5 lists by type the known manufacturers of retroreflective highway sign sheeting.

Table A-3. Comparison of retroreflective sheeting typology classifications.

Specification	TYPOLOGY CLASSIFICATIONS		
	Engineering Grade (EG)	Super Engineering Grade (SEG)	High Performance Grade (HP)
L-S-300C	Reflectivity 1	ns	Reflectivities 2, 4
AASHTO M-268	Class II	ns	Classes IIA, B
FP-85	Type II	Type IIA	Types IIIA, B, C
ASTM D-4956	Type I	Type II	Types III, IV, V

ns - not specified

Table A-4. Comparison of retroreflective sheeting SIA specifications.

Sheeting Color	L-S-300C			AASHTO			FP-85			ASTM			
	EG	SEG	HP	EG	SEG	HP[1]	EG	SEG	HP[2]	EG	SEG	HP III	HP IV
White	80	ns	250	70	ns	250	70	140	250	70	140	250	250
Red	18	ns	45	14.5	ns	45	14.5	30	45	14	30	45	35
Orange	30	ns	100	25	ns	100	25	60	100	25	60	100	100
Yellow	50	ns	170	50	ns	170	50	100	170	50	100	170	170
Green	12	ns	45	9	ns	45	9	30	45	9	30	45	35
Blue	6	ns	20	4	ns	20	4	10	20	4	10	20	20
Brown	25	ns	ns	1	ns	ns	2	5	ns	1	5	ns	7

Notes: ns - not specified
[1] applies to both Type III A & B
[2] applies to Types III A,B,C

Table A-5. Known manufactures of various sheeting types.

Sheeting Type (as per FP-85)				
Type II	Type II A	Type III A	Type III B	Type III C
Avery/Fasson	Seibulite	Seibulite	Stimsonite	Stimsonite
Seibulite	Kiwalite (Sakai Trading)	3M	Reflexite*	
3M				
Kiwalite (Sakai Trading)			–	
American Decal (Adcolite)				

Note:

Type II = Engineering Grade
Type II A = Super Engineering Grade
Type III A = High Performance Grade
Type III B = High Performance Grade (Prismatic)
Type III C = High Performance Grade (Prismatic)
*Construction Work Zone Devices Only

The procedure for testing the SIA of retroreflective sheeting is specified in "Federal Test Method Standard 370, Photometric Measurements of Retroreflective Materials and Retroreflective Devices".(8) Because of the elaborate instrumentation and laboratory set-up this test is not within the capabilities of most small highway agencies. There are however, portable reflectometers which can be used for a quick check of SIA in a sign shop or in the field. Two such devices are the Model 920 and 930 retroreflectometers manufactured by Advanced Retrotechnology Inc. (ARTI) of La Mesa, California.

The ASTM standard E808-81 "Standard Practice for Describing Retroreflection" provides terminology, a geometrical coordinate system, and procedures for designating angles in descriptions of retroreflectors, specification of retroreflector performance and measurements of retroreflection. It is stated in the specification that the geometrical system described is complete and non-redundant and should be used in specifying and testing retroreflectors.

The ASTM Standard E809-81 "Standard Practice for Measuring Photometric Characteristics of Retroreflectors" describes procedures used to measure photometric quantities that relate to the visual perception of retroreflected light. It essentially involves the measurement of normal illuminance at the face of the sample by substituting the photoreceptor for the sample.

The ASTM standard E810-81 "Standard Test Method for Coefficient of Retroreflection of Retroreflective Sheeting" describes the method for instrument measurement of the retroreflective performance of retroreflective sheeting. Measurements made by this test method are related to visual observations of retroreflective sheeting as seen by the human eye when illuminated by tungsten filament light sources. This method is intended as a laboratory test and requires a facility that can be darkened sufficiently so that stray light does not affect the test results.

The ASTM Standard E811-81 "Standard Practice for Measuring Calorimetric Characteristics of Retroreflectors Under Nighttime Conditions" describes a procedure for measuring the color appearance of retroreflectors as seen under nighttime conditions of illumination and viewing. The procedure involves spectral measurements of the incident light and of the retroreflected light under the test-geometry required with either a telecolorimeter or telespectroradiometer.

MOTORISTS NEEDS

The current SIA standards provided in *FP-85* merely reflect the available products and are purchase specifications not necessarily related to driver visibility requirements and environmental conditions.

In order for a traffic sign to be effective it must deliver its information to the driver soon enough to react appropriately and safely. The sight distance requirement of a sign is a function of five components: 1) sign detection, 2) sign recognition, 3) driver decision making, 4) response and 5) completion of maneuver. McGee et al. (9) developed and field tested a decision sight distance model based on detection, recognition, decision making, response and vehicle maneuver. The time requirements for each step were initially estimated based on an extensive literature review, then adjusted according to the findings of an empirical field study. The decision sight distance model elements were later reexamined by Perchonok et al. (10) to develop a version applicable to determining nighttime visibility requirements for retroreflective devices. The model determines minimum detection distance requirement as the summation of distances required for five phases of action. The summation process is based on the assumption that, in the worst case the driver must accomplish each aspect of the process in order, one after the other. This model was formalized by Mace et al. (11) as

a computerized program to evaluate luminance requirement to aid in sign maintenance decisions. This sign maintenance management program models sign visibility requirements in terms of time and distance requirements. However, it does not model the visibility requirements of signs based on human performance capabilities in terms of luminance and contrast needs.

The human visual performance model most generally accepted among highway visibility researchers is that published by the International Commission on Illumination. This model represents an analytic approach to determining detection threshold contrast for a observer adapted to particular surround luminance, with glare and transient adaption requirements accounted for. An object is visible or detectable at threshold level if the objects contrast meets or exceeds the contrast required by an observer when adopted to the luminance of the objects background, also taking into account the effects of disability glare and background luminance that may change over time. This analytic approach to visibility has been incorporated by Bhise (12) into a seeing distance model called DETECT which is a part of the Comprehensive Headlamp Environment Systems Simulation Model (CHESS). The program calculates the threshold visibility distance (50 percent probability of detection) to targets such as delineation, pedestrians, traffic cones, etc. under a wide range of conditions with or without glare from opposing vehicles.

The intent of the FHWA study "Minimum Visibility Requirements for Traffic Control Devices" has been to research the various parts of the information processing model such as detection distance, consipicuity distance, legibility distance, response latency and maneuver time. This minimum visibility study has addressed the issues of individual differences relating to contrast sensitivity and traffic control device differences during the laboratory studies of conspicuity and legibility. After the comparisons between the laboratory and field control

studies, the field validation study, and the minimum visibility model, the minimum visibility requirement for each traffic control device class will be studied.

PERFORMANCE STANDARDS

Drivers require a minimum amount of luminance for both detection and legibility of signs. The specification of minimal luminance requirements for traffic signs has been addressed by a number of researchers. Historically, a sign was considered sufficiently bright if it provided approaching drivers with a minimum of 50 feet of legibility per inch of letter height. However, the selection of 50 ft/in as a minimum legibility distance is quite arbitrary.

Mace (13) suggested that older driver's visibility requirements should be based on a legibility of 40 feet per inch of letter height. Mace also reported that the typical practice in States is to license drivers at 20/40 high-luminance acuity. This acuity level corresponds to a legibility of approximately 30 feet per inch of letter height.

Another approach that has been used is to consider a sign's level of brightness. Sign brightness is considered satisfactory if it provides a legibility distance that is greater than or equal to 85 percent of the maximum obtainable nighttime legibility distance. Like the first approach, the criterion is also too arbitrary as it does not account for the driving situation.

The other measures that have been used to develop the relationship between sign brightness and legibility have been uniformity of sign background, level of internal contrast, and luminance of legend or background. If a sign face degrades unevenly as it ages, then the legibility of the sign is impaired. The Institute of Transportation Engineers recommends a ratio of 5:1 as the maximum acceptable ratio of luminances for externally lighted traffic signs. (14) Another study conducted by Allen et al., (15) concluded that variation in the luminance of different areas of the sign should not be more than 10:1. Another study (16) specifically

designed to establish the relationship between the luminance uniformity of sign background and legibility found that for externally illuminated signs these two variables are significantly correlated only when sign luminance ranges form 9.9 to 39.7 FL. These data indicated that if a reduction in maximum obtainable legibility of 50 percent is assumed to be the maximum acceptable performance decrement, then the maximum acceptable ratio of background luminances is 6:1. However, the luminance of Type II and Type III white sheeting rarely exceed 9.9 FL. For these reasons, the luminance uniformity of background may be relevant to the legibility of illuminated signs but may not be relevant to retroreflective signs.

The contrast between the luminance of the sign legend and the luminance of the sign background is the second measure that has been related to sign brightness and legibility. A common measure of internal contrast is the luminance ratio of the legend and background of the sign, with the greater of the two values used in the numerator of the expression. For signs with a black legend on color background the legibility is determined by the luminance or the color portion of the sign. Therefore, a minimum brightness standard based solely on internal contrast would have little applicability to signs having either a black legend or a black background. Also, most signs will not be taken out of service until there is a complete loss of retroreflectivity, which means that the internal contrast of the sign is essentially fixed for the duration of the sign's service life by the material with which it is constructed. Therefore, internal contrast is most relevant in sign design and construction.

The third measure of sign brightness that can be related to legibility is sign luminance. Legibility as a function of sign luminance has been studied to a greater extent than any other measure of sign brightness. A 1988 study of nighttime conspicuity of highway signs by Olson (17) resulted in recommendations for minimum SIA values for various sign types and in guidance regarding the type of materials to use. The SIA values are based on area

complexity and the required stopping distance for various speeds. The area complexity refers to the ambient light levels in the immediate vicinity of the signing location. The complexity is typically described as low, medium and high corresponding to rural, suburban and urban areas. Table A-6 shows the SIA values of 30" x 30" red STOP signs. Based on those values, engineering grade sheeting would be sufficient for low speed and low complexity areas and high performance sheeting would be required for most situations. For high speed and high complexity areas, supplemental warning signs are warranted. Table A-7 shows the minimum SIA values for warning signs by speed and area complexity derived from the same study. Here, the engineering grade sheeting is sufficient in low-complexity areas. This finding is consistent with the guidelines for warning signs presented by Mace et al. (24). Mace found that engineering grade sheeting degraded to an SIA value of approximately 18 was adequate in low complexity areas. Table A-8 shows the minimum SIA values for overhead guide signs as derived by Olson in the same study. The research by Olson and Mace isolated by speed and area complexity, these signing situations where engineering grade and high performance sheeting are appropriate for roadway signs.

Another study by Morales (18) resulted in recommendation on required overall SIA for STOP signs for various approach speeds under ideal visibility conditions. This study suggests that legibility should not be used as a criteria for developing inservice retroreflective standards for STOP signs and provides mathematical relationships between STOP sign recognition distance and its photometric characteristics. This is based on the fact that due to the unique shape of STOP signs they are recognized and not read to be understood.

A study conducted by the Florida DOT (19) recommended "end of service life" SIA values for various sheeting colors and types. The study used several observers at night in the same vehicle. Each observer recorded when sign detection, shape recognition, color recognition,

Table A-6. Stop sign minimum SIA values.

Recommended Minimum SIA Values for a STOP Sign

Speed (mph)	Stopping Distance (feet)	Area Complexity High	Medium	Low
65	569	*	*	150
60	484	*	*	71
55	407	*	155	30
50	337	170	63	14
45	272	70	25	8
40	215	30	11	4
35	164	16	5	3
30	121	8	3	2

* Supplemental Warning Required

Source: Olson (17)

Table A-7. Warning signs minimum SIA values.

Recommended Minimum SIA Values for Warning Signs (Yellow)

	Area Complexity						
	Low		Medium			High	
Speed	Number of Choices		Number of Choices			Number of Choices	
(mph)	0-3	3 or more	0-1	2-3	3 or more	0-1	2 or more
65	15	31	15	86	630	230	*
60	15	25	15	63	414	173	1115
55	15	21	15	52	276	144	750
50	15	17	15	38	180	110	520
45	15	15	15	29	126	80	345
40	15	15	15	23	80	63	230
35	15	15	15	17	52	52	150
30	15	15	15	15	35	38	100

*Supplementary devices required.

Source: Olson (17)

Table A-8. Overhead guide signs minimum SIA values.

Recommended Minimum SIA Values for Overhead Guide Signs (Green)

Speed (mph)	Area Complexity: Low — Words on Sign 3	6	9	Medium — Words on Sign 3	6	9	High — Words on Sign 3	6	9
70	8	15	27	13	31	70	35	82	200
60	8	13	22	12	25	54	32	70	150
50	7	11	17	11	20	37	28	54	100
40	7	9	13	10	15	25	25	40	68
30	6	8	10	8	12	17	22	33	46

Sign placement is 20 feet high over a 24 foot roadway.

Source: Olson (17)

message recognition, and legibility occurred. The times were converted to distances. Each sign was then screened, thereby reducing SIA, until the sign was determined to be barely adequate. Table A-9 provides the recommended "end of service life" values for white, yellow, green, and red sheeting colors.

The Oregon DOT provides a specification for retroreflection at 7 and 10 years of inservice performance. Under this specification the manufacturer is responsible for all cost in restoring sign panels to the original effectiveness if the retroreflection falls below the values specified in Table A-10. For years 7 and 10 of inservice placement the manufacturer is obligated to replace the sheeting to its original effectiveness if the retroreflectivity falls below the standards listed on the right column of Table A-10. In addition, sign agencies are responsible for dating all signs at the time of installation.

Research has been conducted which is relevant to the question of standards, but standards have not yet been implemented which reflect fundamental driver needs. This is because the problem of specifying luminance standards for traffic signs is complex and multidimensional. Driver requirements of different signs change across situations. Also the population of signs is not uniform in purpose or function. Signs are created in different designs to serve various needs, and these differences create varying levels of luminance requirements for signs to function properly at night.

The ongoing Federal Highway Administration (FHWA) project entitled "Minimum Visibility Requirements for Traffic Control Devices" is to determine the minimum visibility requirements for signs and markings. Based on these minimum visibility requirements, it will be possible to determine the retroreflectivity needed to make a sign visible at a given distance.

Table A-9. End of service life SIA values

Sheeting Color	End of Service Life SIA Values[1]	
	Type II[2]	Type II A, III A, III B[3]
White	40	140
Yellow	16	40
Green	5	5
Red	na	10

na - not available

[1] SIA values measured at 0.2° observation and -4° angles.
[2] Engineering grade sheeting (Type II).
[3] Super-engineering grade (Type II A), high performance (Type III A), and prismatic (Type III B) sheeting.

Source: Florida DOT (19)

Table A-10. Minimum warranties for retroreflective sheeting as specified by Oregon DOT.

Sheeting Color	Minimum Coefficient of Retroreflection (Seven Years)	Minimum Coefficient of Retroreflection (Ten Years)
White	212	200
Yellow	144	136
Green	38	36
Red	38	36
Blue	17	16
Brown	10	9

Another difficulty in the implementation of standards has been an absence of conclusive performance data. The FHWA project entitled "Service Life of Retroreflective Traffic Signs" (20) investigated the relationship between the retroreflectivity performance of sign sheeting with respect to such factors as sheeting age, weather conditions, ground elevation, etc. Based on these relationships, equations were developed to predict approximate inservice SIA of signs. The accuracy of the equations in predicting inservice SIA is limited since the initial SIA values of new sheeting are quite variable.

Finally, there is no fast, practical, and reliable way of measuring luminance in the field, and therefore one cannot easily determine if the requirements are met. The National Cooperative Highway Research Program (NCHRP) study 5-10 "Mobile System for Measuring Retroreflectance of Traffic Signs" (3) has determined the feasibility of developing instrumentation suitable to rapidly measure retroreflectivity from a moving vehicle during daylight hours. A prototype of the system has been constructed and consists of a video camera, electronic flash gun, laser range finder and a data acquisition image analysis system to evaluate the video image for average legend and background retroreflectance. Figure A-5 is a schematic illustration of the system components which are housed in the van shown in Figure A-6. The results of the above three projects and this project will help in development, measurement and implementation of sign performance standards.

SIGN MAINTENANCE PRACTICES

The existing federal standards for luminance of retroreflective materials for traffic signs are purchase specifications and provide no differentiation based upon driver needs. The *Manual on Uniform Traffic Control Devices* (2) simply specifies that all traffic signs be retroreflectorized or illuminated to show the same color and shape by day and night unless

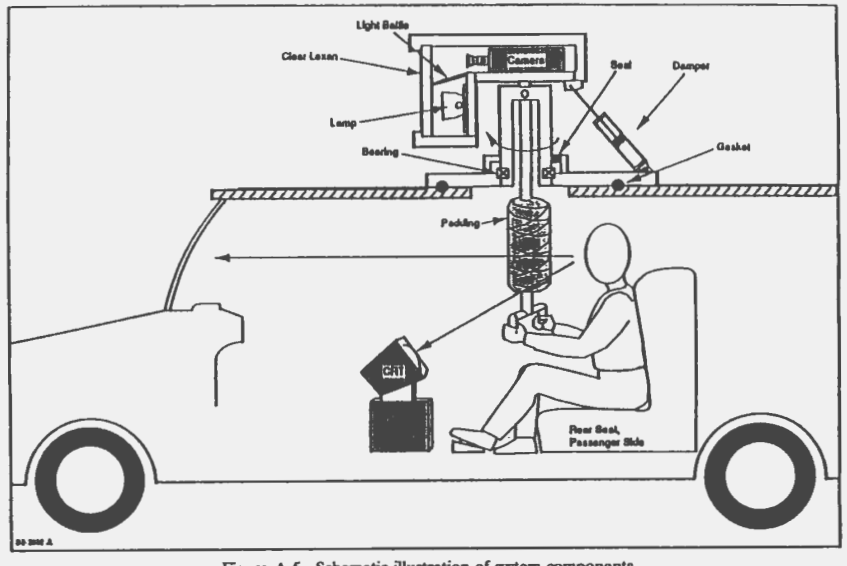


Figure A-5. Schematic illustration of system components.



Figure A-6. Prototype mobile retro-reflectivity measurement system.

specifically excepted in the standards. There are no minimum initial or replacement requirements for retroreflective signs. Based on the agencies surveyed, replacement is left to practices which vary between States, counties and cities. The need for inspection of signs for retroreflectivity is typically not determined under a regimented policy but scheduled by casual, visual inspection. This deficiency is due to the lack of a minimum legibility standards, the competing demands on personnel's times, and the absence of a rapid and reliable retroreflectance measurement device. However, the development of automated sign inventories, minimum performance standards, mobile system for measuring retroreflectance and implementation strategies will provide an opportunity for more efficient and objective solutions to the problems of sign maintenance management.

APPENDIX B—COLLECTION OF RETROREFLECTIVITY DATA

The objective of the national data collection effort was to obtain estimates of sign retroreflectivity conditions across several subgroups including: sign type, sheeting type, and jurisdiction control. To achieve this goal a intensive data collection plan was developed and initiated. The data collection plan addressed the following:

- Identification of key variables
- Determination of sample size
- Selection of study locations
- Development of effective data collection methodology

Each of these data collection plan elements are discussed in the following subsections.

VARIABLES OF INTEREST

Initially, the dependent and independent variables were identified. The dependent variable, the object of effort, was the measure (i.e., SIA value) of retroreflective condition of traffic signs. The independent variables were segregated into four main categories.

1. Geographic Area -- Weather conditions presumably influence the retroreflectivity and service life of sign sheeting. However, as found in the FHWA "Service Life of Retroreflective Traffic Signs" project (20) the effects of climate are difficult to isolate as the climatic influences are very interrelated and tend to disguise the impacts of any specific element. Due to the interrelationship of climatic variables and the influences of highly variable SIA values of new sheeting, the geographic zone system derived for the FHWA project was removed from the final service life models. However, prior to the results of the FHWA project an eight geographic zone system was developed for the data collection effort

described here. It is still reasonable to expect climatic/geographic influences on sheeting deterioration but quantifying these influences remains difficult. The zone system encompassed the continental United States as the goal of this project was to conclude with national estimates of sheeting retroreflectivity conditions.

2. Jurisdiction Levels -- Adopting retroreflectivity standards could have different economic implications depending upon the type and size of jurisdiction. Data was collected across various jurisdiction types to assess the economic impacts of a retroreflectivity standard. The jurisdiction levels identified for sampling were State, county, city, and town/township. The jurisdiction levels generally follow the levels delineated in the Highway Performance Monitoring System (HPMS) from which total roadway mileage was obtained. No data was collected on Federally controlled roadways.

3. Sign Type -- Traffic signs are made of different colors and vary in criticality; therefore, they require different retroreflectivity levels. To accommodate these differences it was necessary to develop the retroreflectivity condition estimates by sign type and color. The MUTCD classifies signs into the following categories:

- Regulatory - black and white, red and white
- Warning - yellow and black
- Guide - green and white, blue and white, brown and white

Data was collected for the following four sign colors by sign type:

- White (Regulatory)
- Red (Regulatory)
- Yellow (Warning)

- Green (Guide)

Parking series regulatory signs and blue, brown, and all street name guide signs were excluded from the sampling effort.

4. Sheeting Type -- Differences exist in retroreflective properties, service life, and per unit cost among sheeting types. Therefore, it was desirable to sample the various types of sheeting. However, from a visual inspection of inservice signs it is possible to distinguish only two types -- enclosed lens sheeting (Types II and II A from *FP-85*) and encapsulated lens sheeting (Type III A). Type II and II A material appear the same during daytime inspection, although in recent years the major manufacturer of Type II A has a symbol on its sheeting that may be distinguishable on some signs. Hence, all signs were identified as either Type II (Engineering Grade) or Type III (High Performance Grade). In the presentation of the results of the condition of signs, this classification was eliminated and all signs of the same color were grouped. Theoretically, the randomness of the data collected resulted in a mix of sheeting types representative of the Nation's population of signs.

SAMPLE SIZE DETERMINATION AND SITE SELECTION

The overall objective of the data collection was to obtain a representative sample of signs for statistically valid estimates of retroreflective condition and of sign density by roadway jurisdiction control. In order to meet the stated objective a sample of different area types, sign types, sign materials, roadway categories, and jurisdiction level of responsibility was needed.

A cluster sampling approach was selected for developing the data collection plan. It involved dividing the population, the entire country, into heterogeneous subgroups or

clusters. States were used to form clusters because they have well defined boundaries. Weather conditions influence the retroreflectivity and service life of signs and, therefore, it was believed that grouping the States by similar weather conditions would be an effective strategy to define the study areas from which to sample. The eight geographic zones developed for the FHWA "Service Life of Retroreflective Traffic Signs" project were modified slightly to maintain state boundary lines. This zone system considers general climatic conditions and solar radiation levels.

Within each zone a minimum of two primary sampling units (PSU) were selected. Each PSU needed at least three different jurisdictions (city, county, State or town). Individual counties were selected as the most appropriate PSU. Using FHWA's HPMS data, counties with three or more different jurisdictions were segregated. The counties were further segregated by urban and rural designations based on population density.

Establishing the sample size usually involves trading off statistical requirements against time and funds available. Using cost and variance models alternate combinations of total PSUs and roadway segments were selected. The cost model is described as follows:

$$\text{Total Budget} = (Cpsu)(M) + (Cseg)(M)(N)$$

where:

Cpsu = Cost per sampled PSU

M = Number of PSUs

Cseg = Cost per sampled segment

N = Number of segments within each PSU

Judgement was used to select the following reasonable alternatives:

- 10 PSUs and 40 segments
- 25 PSUs and 12 segments
- 40 PSUs and 5 segments

Each of these alternatives satisfied the budget constraints.

A variance model was developed to evaluate the variance in SIA conditions between PSUs and within PSUs. The goal of the model was to establish if the between or within variance is greater and then optimize the sample of PSUs and segments. The variance model had the following form:

$$V^2(x) = B^2/m + W^2/mn$$

where:

$V^2(x)$ = Total variance

B^2 = Between PSU variance

W^2 = Within PSU variance

m = Number of PSUs

n = Number of segments

B^2 and W^2 were estimated from data obtained from the FHWA "Service Life of Retroreflective Traffic Signs" project. B^2 and W^2 vary by sheeting color and type. B^2 was found greater than W^2; therefore, it was concluded to increase the number of PSUs rather than increase the number of segments within each PSU. Table B-1 provides the variance estimates for several alternate design options. It was determined to sample 25 PSUs with 12 segments in each PSU, as minimal improvement in variance was afforded beyond 25 PSUs.

Table B-1. Estimated variance for three sample designs.

Sheeting Color and Type	Estimated Variance Number PSUs Number of segments 10 40	 25 12	 40 5
Red			
-EG	3.0	1.7	1.6
-HP	7.8	4.0	3.5
White			
-EG	19.8	10.8	10.4
-HP	30.6	17.2	17.0
Yellow			
-EG	13.5	12.0	14.0
-HP	17.0	2.0	2.6
Green			
-EG	2.3	2.0	2.6
-HP	7.0	3.1	2.2

Note: EG = engineering grade sheeting
HP = high performance sheeting

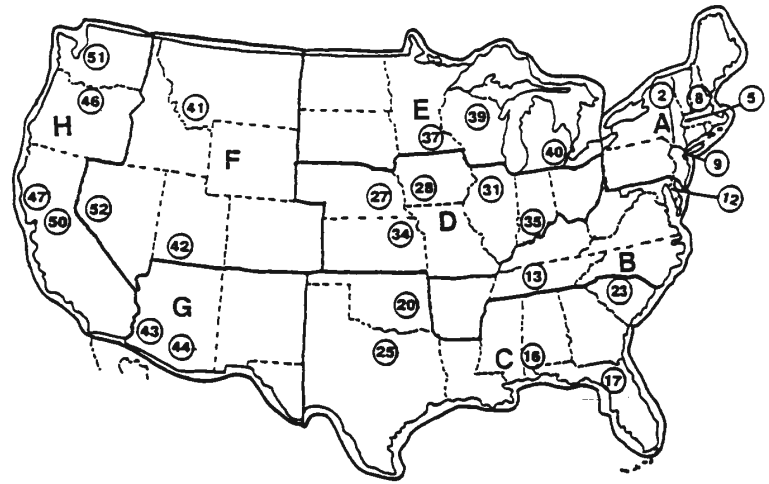
Also, as the number of PSUs increases the total signs to sample greatly decreases.

The 25 PSUs were allocated to the eight zones based on that zone's proportion of total national roadway mileage. Depending on the number of different jurisdiction roadways (i.e. State, county, city or town/township) within a county, four or five segments were selected for each jurisdiction type. The roadway segments under each jurisdiction within a county were identified on county mapping. Approximately 15 traffic signs per segment were measured. Given a starting point on a segment the first 15 traffic signs were selected and measured to insure randomness.

The candidate counties were screened for three or more different jurisdictions roadways and for urban and rural population densities. From the screened list, counties were then randomly selected using the HPMS numbering system. At least one rural and one urban county were selected in each zone. Again, the total number of PSUs per zone was determined by the total roadway mileage. Certain manual selections were necessary for travel and logistical considerations. Figure B-1 provides the geographic location of the data collection sites with the zone system boundaries. As shown 28 sites, or 3 more than the original plan, were actually sampled. This was attributed to the efficiency of the data collection crews.

DATA COLLECTION METHOD

Two teams of two technicians each were used to collect the retroreflectivity data throughout the country. The Advanced Retrotechnology model 920 retroreflectometer with extension pole and remote display was used to collect the measurements. The traffic signs were not cleaned prior to measurement because it was desirable to measure the



Data Collection Sites (County)

Delaware, NY (2)	Shawnee, KS (34)
Berkshire, MA (5)	Vanderburgh, IN (35)
Hillsborough, NH (8)	Fillmore, MN (37)
Westchester, NY (9)	Oneida, WI (39)
Calvert, MD (12)	Wayne, MI (40)
Montgomery, TN (13)	Madison, MT (41)
Washington, AL (16)	Iron, UT (42)
Levy, FL (17)	Yuma, AZ (43)
Pittsburg, OK (20)	Pima, AZ (44)
Greensville, SC (23)	Wasco (46)
Dallas, TX (25)	Mendocino, CA (47)
Butler, NE (27)	Sacramento, CA (50)
Adair, IA (28)	King, WA (51)
Bureau, IL (31)	Clark, NV (52)

Figure B-1. Location of data collection sites.

retroreflectivity as the drivers view the sign. (The FHWA "Service Life of Retroreflective Traffic Signs" project found that sign washing increased SIA by 12% and 8% for Type II and Type III A sheeting signs, respectively). The retroreflectivity readings, segment and county coding, sheeting color, and sheeting type were manually recorded in the field and transferred to computer database in the office. Four readings per sign were taken and later averaged.

APPENDIX C—QUESTIONNAIRE SURVEY RESULTS

Questionnaire surveys were used to obtain data including: sign population, existence of sign inventory, sign replacement costs, sign maintenance costs, inventory inputs, etc. The surveys were distributed to 50 state, 790 county and 85 city agencies. Responses were received from 48 states, 170 counties, and 20 cities.

The following paragraphs provide a summary of the responses to key questions. The summary of responses is grouped into two areas -- 1) sign inventory and 2) replacement and maintenance.

SIGN INVENTORY

Question A. Does your agency have a sign inventory?

Agency	Yes	No
State	14	33
County	129*	41
City	13*	7

* This is not the result of a random sample of jurisdictions. Those agencies with computer inventories were more likely to respond to the questionnaire survey.

Only 30 percent of state agencies were found to maintain statewide sign inventories. For counties and cities, generalizations cannot be made from the survey because this was not a random sample of these agencies. However, from the considerable contact with local jurisdictions it can be stated that few of these agencies maintain inventory systems.

Question B. What is your inventory format?

Format	State	Agency: County	Agency: City
Card/Paper	11%	43%	24%
Main/Mini Computer	37%	20%	23%
Micro Computer	48%	32%	30%
Other (photolog,maps,etc.)	4%	5%	15%

Approximately 85 percent of statewide inventories are computerized. Only approximately 50 to 60 percent of the counties and cities responding with inventories had computerized systems. Over 40 percent of the counties responding as having inventories maintained card or paper records. The majority of the "other" responses were inventories on aerial photography and other mapping materials. The percentage of county and city agencies having micro-computer format is likely to increase as these programs are becoming readily available.

Question C. Does your inventory include the following elements?

Data Element	State	Agency: County	Agency: City
Sign Type	93%	97%	92%
Installation Date	78%	82%	77%
Replacement Date	74%	83%	77%
Sheeting Type	56%	50%	54%

SIGN REPLACEMENT AND MAINTENANCE

Question D. Approximately how many signs do you replace per year due to vandalism, knockdown, poor retroreflectivity and other causes?

Reason for Replacement	Percent of All Replacement: Agency: County	Agency: City
Vandalism and Theft	39%	24%
Knockdown	23%	27%
Poor Retroreflectivity	16%	30%
Other	22%	19%

Question E. What is your total annual cost for sign maintenance and replacement?

Item	County: Average Cost	County: No. of Responses	City: Average Cost	City: No. of Responses
Total Cost	$96,000	148	$277,000	16
Per Mile Cost	$92.00	141	$132.30	10
Per Capita Cost	$1.00	72	$1.20	16

Question F. What is your average cost to replace a sign?

Item	County: Average Cost	County: No. of Responses	City: Average Cost	City: No. of Responses
Materials Cost/SF	$ 5.17	7	NA	0
Labor Cost/Hour	$14.97	19	NA	0
Equipment Cost/Hour	$10.35	16	NA	0
Material Cost/Sign	$38.24	117	$29.56	17
Labor Cost/Sign	$18.92	103	$14.49	14
Equipment Cost/Sign	$10.81	98	$ 9.84	13
Total Cost/Sign	$65.72	168	$54.66	13

NA - Not Available

Question G. How many traffic signs are under the control of your agency?

ITEM	TOTAL SIGNS PER CAPITA AND PER MILE[1]							
	COUNTY				CITY			
	Signs Per 100 Persons	No. of Responses	Signs Per Mile	No. of Responses	Signs Per 100 Persons	No. of Responses	Signs Per Mile	No. of Responses
Regulatory Signs[2]	7.1	35	3.7	39	7.0	13	18.2	12
Warning Signs	6.3	35	4.3	39	3.8	12	9.8	11
Guide Signs[3]	2.0	32	2.6	36	0.6	11	1.2	11
Total Signs	17.6	42	11.9	45	22.6	17	63.9	16

[1]Includes actual and estimated sign totals
[2]Does not include parking series signs
[3]Does not include street name signs

The replacement cost and sign density information obtained here became the basis for the economic analysis and the development of the implementation strategies.

APPENDIX D—SIGN REPLACEMENT COSTS

Sign replacement cost for State, county, city, and town controlled roadways were developed for red, yellow, green, and white sheeting based on the minimum SIA criteria identified in Chapter 3. Each sheeting color was tested using the lower and upper minimum SIA standards. The economic model was run for a total of 11 years to obtain the annual replacement costs for the years after implementation of the minimum standards.

Tables D-1, D-2, D-3, and D-4 provide the sign replacement cost in terms of dollars per roadway mile for State, county, city, and town controlled roadways, respectively. The shaded boxes in the tables highlight the annual replacement costs for each year of the implementation schedule. The unshaded boxes show the annual cost to maintain the minimum standards after implementation is completed.

There is a considerable difference in replacement costs between the lower and upper standards, especially for the red, green, and white sheeting. The replacement cost for green sheeting represents 65 to 75 percent of the total replacement cost. Several reasons for this are apparent:

1. Average cost per sign to replace green guide signs is nearly twice the of standard warning and regulatory signs due to sign size.
2. Majority of green guide signs are constructed using engineering grade sheeting which has lower retroreflectivity characteristics than the other sheeting types.
3. Minimum retroreflectivity standards for green sheeting tested here were high and in the case of the upper value (i.e. 10 SIA) higher than the delivered new specification for green, engineering grade sheeting listed in *FP-85*.
4. Many of the green sheeting samples collected across the country had SIA values less than 8 SIA which was the lower minimum standard tested here.

Table D-1 Sign replacement costs for state roadways.

		RED				YELLOW				GREEN				WHITE			
	State	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile
Lower Standards	Year 1	22	14	17	21	2	5	5	8	156	69	48	39	6	3	2	4
	Year 2	10	14	17	21	2	5	5	8	20	69	48	39	1	3	2	4
	Year 3	11	14	17	21	4	5	5	8	33	69	48	39	1	3	2	4
	Year 4	16	16	17	21	4	4	5	8	10	10	48	39	1	1	2	4
	Year 5	27	27	17	21	8	8	5	8	20	20	48	39	3	3	2	4
	Year 6	26	26	26	21	8	8	8	8	30	30	30	39	4	4	4	4
	Year 7	21	21	21	21	10	10	10	8	28	28	28	39	4	4	4	4
	Year 8	16	16	16	21	11	11	11	8	43	43	43	39	5	5	5	4
	Year 9	31	31	31	21	8	8	8	8	30	30	30	39	5	5	5	4
	Year 10	25	25	25	21	13	13	13	8	20	20	20	39	7	7	7	4
	Year 11	30	30	30	30	6	6	6	6	40	40	40	40	4	4	4	4
Upper Standards	Year 1	167	83	62	46	83	48	32	24	221	90	60	45	18	9	6	7
	Year 2	17	83	62	46	20	48	32	24	20	90	60	45	4	9	6	7
	Year 3	66	83	62	46	16	48	32	24	30	90	60	45	6	9	6	7
	Year 4	23	23	62	46	21	21	32	24	25	25	60	45	6	6	6	7
	Year 5	39	39	62	46	19	19	32	24	43	43	60	45	5	5	6	7
	Year 6	23	23	23	46	13	13	13	24	30	30	30	45	5	5	5	7
	Year 7	35	35	35	46	14	14	14	24	30	30	30	45	5	5	5	7
	Year 8	32	32	32	46	9	9	9	24	28	28	28	45	5	5	5	7
	Year 9	40	40	40	46	33	33	33	24	15	15	15	45	6	6	6	7
	Year 10	38	38	38	46	11	11	11	24	10	10	10	45	9	9	9	7
	Year 11	30	30	30	30	13	13	13	13	93	93	93	93	4	4	4	4

Table D-2 Sign replacement costs for county roadways.

		RED				YELLOW				GREEN				WHITE			
	County	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile
Lower Standards	Year 1	17	12	14	19	18	8	7	8	160	75	52	38	6	3	2	3
	Year 2	9	12	14	19	1	8	7	8	36	75	52	38	1	3	2	3
	Year 3	10	12	14	19	4	8	7	8	29	75	52	38	2	3	2	3
	Year 4	20	20	14	19	4	4	7	8	15	15	52	38	1	1	2	3
	Year 5	16	16	14	19	6	6	7	8	22	22	52	38	2	2	2	3
	Year 6	20	20	20	19	4	4	4	8	15	15	15	38	2	2	2	3
	Year 7	27	27	27	19	8	8	8	8	36	36	36	38	4	4	4	3
	Year 8	21	21	21	19	10	10	10	8	7	7	7	38	3	3	3	3
	Year 9	25	25	25	19	17	17	17	8	36	36	36	38	5	5	5	3
	Year 10	27	27	27	19	11	11	11	8	22	22	22	38	4	4	4	3
	Year 11	27	27	27	27	15	15	15	15	22	22	22	22	6	6	6	6
Upper Standards	Year 1	166	89	66	45	101	46	34	28	247	92	63	44	18	8	7	7
	Year 2	26	89	66	45	17	46	34	28	22	92	63	44	4	8	7	7
	Year 3	75	89	66	45	21	46	34	28	7	92	63	44	4	8	7	7
	Year 4	23	23	66	45	18	18	34	28	36	36	63	44	4	4	7	7
	Year 5	39	39	66	45	15	15	34	28	15	15	63	44	4	4	7	7
	Year 6	18	18	18	45	21	21	21	28	22	22	22	44	6	6	6	7
	Year 7	35	35	35	45	21	21	21	28	29	29	29	44	7	7	7	7
	Year 8	19	19	19	45	13	13	13	28	15	15	15	44	7	7	7	7
	Year 9	24	24	24	45	45	45	45	28	36	36	36	44	7	7	7	7
	Year 10	23	23	23	45	11	11	11	28	7	7	7	44	10	10	10	7
	Year 11	18	18	18	18	14	14	14	14	102	102	102	102	5	5	5	5

Table D-3 Sign replacement costs for city roadways.

		RED				YELLOW				GREEN				WHITE			
	City	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile
	Year 1	73	34	27	22	45	16	13	13	141	83	78	52	16	6	5	6
	Year 2	14	34	27	22	0	16	13	13	78	83	78	52	1	6	5	6
Lower	Year 3	13	34	27	22	3	16	13	13	31	83	78	52	2	6	5	6
Standards	Year 4	11	11	27	22	8	8	13	13	63	63	78	52	3	3	5	6
	Year 5	20	20	27	22	7	7	13	13	63	63	78	52	4	4	5	6
	Year 6	21	21	21	22	8	8	8	13	78	78	78	52	5	5	5	6
	Year 7	17	17	17	22	7	7	7	13	16	16	16	52	5	5	5	6
	Year 8	15	15	15	22	16	16	16	13	31	31	31	52	7	7	7	6
	Year 9	19	19	19	22	15	15	15	13	0	0	0	52	6	6	6	6
	Year 10	14	14	14	22	19	19	19	13	16	16	16	52	8	8	8	6
	Year 11	11	11	11	11	31	31	31	31	31	31	31	31	7	7	7	7
	Year 1	213	99	69	44	184	68	48	35	313	151	100	55	33	15	12	10
	Year 2	4	99	69	44	18	68	48	35	63	151	100	55	6	15	12	10
Upper	Year 3	80	99	69	44	23	68	48	35	78	151	100	55	7	15	12	10
Standards	Year 4	8	8	69	44	21	21	48	35	16	16	100	55	7	7	12	10
	Year 5	39	39	69	44	14	14	48	35	31	31	100	55	7	7	12	10
	Year 6	16	16	16	44	12	12	12	35	0	0	0	55	6	6	6	10
	Year 7	22	22	22	44	8	8	8	35	31	31	31	55	6	6	6	10
	Year 8	15	15	15	44	8	8	8	35	16	16	16	55	6	6	6	10
	Year 9	21	21	21	44	64	64	64	35	0	0	0	55	6	6	6	10
	Year 10	20	20	20	44	15	15	15	35	0	0	0	55	13	13	13	10
	Year 11	19	19	19	19	12	12	12	12	125	125	125	125	3	3	3	3

Table D-4 Sign replacement costs for town roadways.

		RED				YELLOW				GREEN				WHITE			
	Town	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile	One Yr $/Mile	3 Yrs $/Mile	5 Yrs $/Mile	10 Yrs $/Mile
	Year 1	39	23	17	15	1	0	0	3	129	62	70	50	3	1	2	3
	Year 2	21	23	17	15	0	0	0	3	37	62	70	50	0	1	2	3
Lower	Year 3	8	23	17	15	0	0	0	3	18	62	70	50	1	1	2	3
Standards	Year 4	9	9	17	15	0	0	0	3	55	55	70	50	2	2	2	3
	Year 5	9	9	17	15	0	0	0	3	111	111	70	50	3	3	2	3
	Year 6	12	12	12	15	3	3	3	3	55	55	55	50	3	3	3	3
	Year 7	18	18	18	15	6	6	6	3	37	37	37	50	2	2	2	3
	Year 8	9	9	9	15	9	9	9	3	18	18	18	50	4	4	4	3
	Year 9	15	15	15	15	19	19	19	3	37	37	37	50	2	2	2	3
	Year 10	14	14	14	15	12	12	12	3	0	0	0	50	4	4	4	3
	Year 11	14	14	14	14	19	19	19	19	37	37	37	37	4	4	4	4
	Year 1	134	66	52	36	71	33	28	24	235	142	96	55	16	7	5	7
	Year 2	12	66	52	36	16	33	28	24	92	142	96	55	2	7	5	7
Upper	Year 3	58	66	52	36	12	33	28	24	74	142	96	55	4	7	5	7
Standards	Year 4	18	18	52	36	19	19	28	24	18	18	96	55	3	3	5	7
	Year 5	38	38	52	36	21	21	28	24	37	37	96	55	4	4	5	7
	Year 6	32	32	32	36	13	13	13	24	18	18	18	55	5	5	5	7
	Year 7	24	24	24	36	18	18	18	24	0	0	0	55	8	8	8	7
	Year 8	17	17	17	36	18	18	18	24	18	18	18	55	10	10	10	7
	Year 9	14	14	14	36	34	34	34	24	0	0	0	55	9	9	9	7
	Year 10	14	14	14	36	16	16	16	24	37	37	37	55	11	11	11	7
	Year 11	15	15	15	15	15	15	15	15	129	129	129	129	6	6	6	6

On all roadways the need for replacement of red sheeting signs was quite high. The problems of color fade of this sheeting type contributes to the overall poor condition of these signs. In several instances the annual maintenance cost actually increased after the implementation schedule was completed. The population of signs for this evaluation was deteriorated using the equations and relationships developed in FHWA's "Service Life of Retroreflective Traffic Signs". High annual costs after the standards implementation are the product of a large population of signs of similar age (i.e., 5 or more years) failing to meet the minimum in the years after the schedule has been fulfilled.

REFERENCES

1. Advanced Notice of Proposed Amendment to Manual on Uniform Traffic Control Devices. Federal Highway Administration, Federal Register.
2. *Manual on Uniform Traffic Control Devices for Streets and Highways.* U.S. Department of Transportation, Federal Highway Administration, Washington, D.C. (1988).
3. LUMIA, J.J., "A Mobile System for Measuring Retroreflectance of Traffic Signs." NCHRP Project 5-10 (Feb. 1989).
4. MCGEE, H.W. and MACE, D.L., "Retroreflectivity of Roadway Signs for Adequate Visibility: A Guide." *Report No. FHWA/DF-88/001,* Federal Highway Administration, Office of Direct Federal Programs (Nov. 1987).
5. CUNARD, R.A., "Maintenance Management of Street and Highway Signs." *NCHRP Synthesis of Highway Practice 157.* Transportation Research Board, National Research Council, Washington, D.C. (Sept. 1990).
6. *Guide to the Properties and Uses of Retroreflectors at Night., Publication CIE No. 72.,* International Commission on Illumination, Vienna, Austria (1987).
7. *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, FP-85.* U.S. Department of Transportation, Federal Highway Administration (1985).
8. Federal Test Method Standard, "Instrumental Photometric Measurements of Retroreflective Material and Retroreflective Devices" (Mar. 1977).
9. MCGEE, H.W., MOORE, W., KNAPP, B.G., and SONDERS, J.H., "Decision Sight Distance for Highway Design and Traffic Control Requirements." *Report No. FHWA/RD-78/78,* Federal Highway Administration, Washington, D.C. (Feb. 1978).
10. PERCHONOK, K., and POLLACK, L., "Luminous Requirements for Traffic Signs." Interim Report, Institute for Research, State College, Pennsylvania (Dec. 1981).
11. MACE, D.J. ET AL., "Traffic Signs in Complex Visual Environments." *Report No. FHWA/RD-82/102* (Nov. 1982).
12. BHISE, V.D., ET AL., "Modeling Vision with Headlights in a System Context." *Society of Automobile Engineers, No. 770238* (Mar. 1977).
13. MACE, D.J., "Sign Legibility and Conspicuity." *Transportation Research Board, Special Report 218,* Vol. 2 (1988) pp. 270–293.
14. Institute of Transportation Engineers, Technical Committee 7-C, "Traffic Sign Illumination with External Fluorescent Fixtures." *Traffic Engineering 30,* No. 6 (Mar. 1960).
15. ALLEN, T.M., ET AL., "Luminance Requirements for Illuminated Signs." *Highway Research Record 179* (1967).
16. DAHLSEDT, S., "Luminance Uniformity and Legibility of Traffic Signs." *Lighting Research and Technology 6,* No. 4 (1974).
17. OLSON, P.L., "Minimum Requirements for Adequate Nightline Conspicuity of Highway Signs." The University of Michigan Transportation Research Institute, Ann Arbor, Michigan, *UNTRI-88-8* (1988).
18. MORALES, J.M., "Retroreflective Requirements for Traffic Signs—A Stop Sign Case Study." *Report No. FHWA/RD-87-017* (Jan. 1987).
19. WAGNER, J.A., "Investigation of the Legibility of Sign Letter and Background Type Combinations Under Various Conditions of Weather and Viewing and Durability of Reflective Sheeting." Florida Department of Transportation, *FL/DOT/SMO/357-89* (1989).
20. BLACK, K.L., ET AL., "Service Life of Retroreflective Traffic Signs." *FHWA-RD-90-101* (Mar. 1991).
21. LAGERGREN, E., "Traffic Sign Retroreflectivity Measurements Using Human Observers." Washington State Department of Transportation, *WA-RD 140.1* (1987).
22. DATTA, T.K., TSUCHIYAMA, K.H., and OPIELA, K.S., "Cost-Effective Inventory Procedures for Highway Inventory Data." *Report No. DTFH61-83-C-00043,* U.S. Department of Transportation, Federal Highway Administration, Washington, D.C. (June 1985).
23. DATTA, T.K., and HERF, L., "Cost-Effectiveness Analysis for Various Inventory Procedures." *ITE J.,* Institute of Transportation Engineers, Washington, D.C. (Sept. 1986).
24. MACE, D.J., ET AL., "Sign Luminance Requirements for Various Background Complexities." Institute for Research, State College, Pennsylvania, *Report FHWA/RD-85/056* (Sept. 1985).
25. "County Road Mileage." Highway Performance Monitoring System, U.S. Department of Transportation, Transportation Computer Center (1987).

APPENDIX D

TRANSPORTATION RESEARCH

RECORD

No. 1421

Highway Operations, Capacity, and Traffic Control

Traffic Control Devices, Visibility, and Traffic Signal Systems

LINDA HALL
JAN 9 1995

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

TRANSPORTATION RESEARCH

RECORD

No. 1421

Highway Operations,
Capacity, and Traffic Control

Traffic Control Devices, Visibility, and Traffic Signal Systems

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. 1993

Transportation Research Record 1421
ISSN 0361-1981
ISBN 0-309-05574-1
Price: $26.00

Subscriber Category
IVA highway operations, capacity, and traffic control

TRB Publications Staff
Director of Reports and Editorial Services: Nancy A. Ackerman
Associate Editor/Supervisor: Luanne Crayton
Associate Editors: Naomi Kassabian, Alison G. Tobias
Assistant Editors: Susan E. G. Brown, Norman Solomon
Office Manager: Phyllis D. Barber
Senior Production Assistant: Betty L. Hawkins

Printed in the United States of America

Sponsorship of Transportation Research Record 1421

GROUP 3—OPERATION, SAFETY, AND MAINTENANCE OF TRANSPORTATION FACILITIES
Chairman: Jerome W. Hall, University of New Mexico

Facilities and Operations Section
Chairman: Jack L. Kay, JHK & Associates

Committee on Traffic Control Devices
Chairman: Jonathan Upchurch, Arizona State University
Secretary: W. Scott Wainwright, Montgomery County Department of Transportation
Arthur H. Breneman, Linda L. Brown, Benjamin H. Cottrell, Jr., P. Norman Deitch, Robert E. Dewar, Daniel J. Gilliam, Robert L. Gordon, Mohammad M. Khan, Feng-Bor Lin, Richard W. Lyles, Errol C. Noel, A. Essam Radwan, Lewis Rhodes, Stephen H. Richards, Robert K. Seyfried, Steven R. Shapiro, Harry B. Skinner, Howard S. Stein, Dwight L. Stevens, James A. Thompson, Gerald Ullman

Committee on Visibility
Chairman: John B. Arens, Federal Highway Administration
Peter G. Contos, Eugene Farber, Mark Freedman, Donald C. Harris, S. Allen Heenan, Ronald J. Hensen, Antanas Ketvirtis, L. Ellis King, Ken F. Kobetsky, David A. Kuemmel, Douglas J. Mace, Marc B. Mandler, Richard A. Mather, Herbert A. Odle, Richard Arnold Olsen, Justin J. Rennilson, Duco A. Schreuder, Richard N. Schwab, Richard E. Stark, Robert R. Wylie, Helmut T. Zwahlen

Committee on Traffic Signal Systems
Chairman: Herman E. Haenel, Advanced Traffic Engineering
Secretary: Alberto J. Santiago, Federal Highway Administration
A. Graham Bullen, E. Ryerson Case, Edmond Chin-Ping Chang, David J. Clowes, Robert A. De Santo, Donald W. Dey, Gary Duncan, Nathan H. Gartner, Robert David Henry, Dallas W. Hildebrand, Paul P. Jovanis, Les Kelman, Alfred H. Kosik, Joseph K. Lam, Feng-Bor Lin, David C. Powell, Raymond S. Pusey, Dennis I. Robertson, Lionel M. Rodgers, Stephen Edwin Rowe, Tom L. Stout, Miroslav Supitar, James A. Thompson, Charles E. Wallace

Richard A. Cunard, Transportation Research Board staff

Sponsorship is indicated by a footnote at the end of each paper. The organizational units, officers, and members are as of December 31, 1992.

Transportation Research Record 1421

Contents

Foreword v

Operational Comparison of Leading and Lagging Left Turns 1
Jim C. Lee, Robert H. Wortman, David J. P. Hook, and Mark J. Poppe

Selection Criteria for Left-Turn Phasing and Indication Sequence 11
Seth A. Asante, Siamak A. Ardekani, and James C. Williams

Analysis of Flashing Signal Operation 21
Kent C. Kacir, Robert J. Benz, and H. Gene Hawkins, Jr.

Microscopic Simulation Modeling of Minimum Thresholds Warranting Intersection Signalization 30
Anthony A. Saka

Development of an Emergency Zone Sign 36
Martin T. Pietrucha

Evaluation of the Federal Vision Standard for Commercial Motor Vehicle Operators 45
Lawrence E. Decina and Michael E. Breton

Entrance Angle Requirements for Retroreflectorized Traffic Signs 53
Michael S. Griffith, Jeffrey F. Paniati, and Richard C. Hanley

Exact Road Geometry Output Program for Retroreflective Road Sign Performance 61
Kenneth D. Uding

Decision Support System for Controlling Traffic Signals 69
Ayelet Gal-Tzur, David Mahalel, and Joseph N. Prashker

Methodology for Evaluating Traffic Detector Designs 76
James A. Bonneson and Patrick T. McCoy

PASSER IV: A Program for Optimizing Signal Timing in Grid Networks 82
Nadeem A. Chaudhary and Carroll J. Messer
DISCUSSION, *Nathan H. Gartner and John D. C. Little*, 91
AUTHORS' CLOSURE, 92

Enhancements to the PASSER II-90 Delay Estimation Procedures 94
Meher P. Malakapalli and Carroll J. Messer

Hybrid Genetic Algorithm To Optimize Signal Phasing and Timing 104
Mohammed A. Hadi and Charles E. Wallace

Exact Road Geometry Output Program for Retroreflective Road Sign Performance

KENNETH D. UDING

The angles used for the laboratory testing of retroreflective sign sheeting that are set forth in specifications are well defined and are well understood in the laboratory test setting. Not well known is exactly what values of these angular parameters, especially observation angle, occur for actual signs on the roadway. The mathematics for a complete vector structure incorporating the location data for headlamps, driver's eye, the sign, and the vehicle-to-sign (road) distance has been set up. These inputs define all locations exactly; there are no assumptions. The mathematics has been incorporated into a computer program, ERGO (Exact Road Geometry Output), which computes the exact angles at which the sign is actually seen by approaching drivers. The observation angle for actual signs is shown to be two separate values—one for each headlamp—and not simply the eye height over the headlamps. Eye setback is also shown to be a critical factor under some conditions. The ERGO data demonstrate that observation angle is a direct function of road distance: as road distance becomes less, observation angle becomes greater. Specific observation angles correspond to specific road distances. Graphs of the observation and entrance angle correlates are given for STOP and near-roadside signs, overhead guide signs, and signs at a large offset from the road edge. The effect of different size vehicles on observation angle is shown. The relationship of time to observation angle is demonstrated: as the approaching driver observes a sign at observation angles greater than 0.5 degree, these angles are traversed in fractions of a second. Both the ERGO program and its mathematical basis will be made available to others so that it can be applied to other experimental and theoretical data to better correlate laboratory test values and actual road performance of retroreflective material.

Road signs at night require some minimum level of luminance in order to be seen effectively and in time by an approaching driver who is dependent on reading such signs for certain essential information. Retroreflective sheeting is used on road traffic signs as a means to provide this luminance in the absence of internal or external illumination. Specifications for minimum reflectivity values in laboratory tests of this sheeting have the ultimate objective of providing the required level of effective performance (i.e., luminance) for such signs at the distances and for the time that the driver requires. The efficiency of retroreflective sheeting is specified by setting reflective efficiency (coefficient of retroreflection) values (R_A) for certain laboratory test points determined by designating values for those angular parameters that have been carefully defined for laboratory tests (*1*; ASTM Standard E808-91; AASHTO Standard Method of Test T257-86). The angular parameters that are recognized as the primary determinants of reflective efficiency and are set forth in every specification are observation angle and entrance angle. These angular parameters must be carefully determined and accurately set up in the laboratory to ensure accurate and valid measurements of the reflectivity (as well as to achieve correlation between laboratories). An R_A-value associated with a certain reflective sheeting has meaning only in the context of the *pair* of these angular values at which it is measured: one exact observation angle and one exact entrance angle. (The "one entrance angle" may be defined by the two angular coordinates B_1 and B_2, which, taken together, define a single entrance angle condition.) These angles are well defined and well understood for laboratory test purposes. What is not well understood is what the actual observation and entrance angles are that occur on the roadway in specific sign situations. How are these angles determined for actual road signs seen by the driver of a vehicle? How do these angles change as the vehicle approaches the sign? What angular values are important to a driver approaching a particular sign? How are these values different for drivers of different types of vehicles?

In a recently published National Cooperative Highway Research Program (NCHRP) Report (*2*), it was pointed out that the federal standard (then FP-85) does provide minimum specific intensity per unit area (SIA) (R_A) standards for new material. These standards, however, were developed by sheeting manufacturers as purchase specifications, not based on drivers' needs. Therefore, in order to set a new standard for sheeting based on the driver's actual minimum visibility requirements, the report stated:

> The FHWA project on 'Minimum Visibility Requirements for Traffic Control Devices,' is to determine the minimum visibility distances for signs and markings. Based on these minimum visibility requirements, it will be possible to determine the retroreflectivity necessary to make a sign or marking visible at a given distance.

A parallel effort is under way by the European Committtee for Coordination of Standards CEN to develop a standard based on the luminance requirements for reading actual road signs. This effort is equally dependent on accurate values for the observation and entrance angles at which those signs are actually seen by drivers if it is to arrive at specification values that correlate with the actual performance as planned.

A method is needed that can readily provide accurate observation and entrance angle correlates for given sign situations and at different viewing distances. These measurement parameters can then easily be included in study data and considered in arriving at conclusions relating reflectivity levels and other variables. Although some researchers may be computing these values accurately, the basis of such values is never certain and almost never is it adequately described.

Stimsonite Corporation, 7542 N. Natchez, Niles, Ill. 60648.

Thus computational error or the dimensional basis cannot be determined or verified. A search of the literature reveals no data on any such method generally available to accurately determine these angular values. There does not appear to be any detailed compilation of these values for actual road sign locations and viewing distances.

Consequently, the computer program ERGO (Exact Road Geometry Output) has been developed to determine the exact observation and entrance angle correlates that actually occur for signs and traffic control devices at different locations and distances, as well as values for several other angular parameters of retroreflectivity. ERGO is available at no charge to qualified personnel interested in the use or study of retroreflective sheeting. Its structure and formulas are available for analysis and proof. It can be used as a common reference for other experimental data.

The data obtained with ERGO are discussed in this paper. Summaries in the form of graphs of the observation and entrance angle correlates for some typical signs are shown. These "applications" of ERGO data illustrate how the data can be useful in studying how the angular parameters change in real road sign situations. In turn, this may be essential in the determination of valid measurement values for minimum levels of retroreflectivity. Given a sufficient range of retroreflectivity data, the program may be used to accurately compare the efficiency of different retroreflective materials for particular applications.

ERGO OPERATION

To calculate the exact road geometry, a simple mathematical vector structure was created together with the formulas to compute all angles precisely and accurately. The computer program was written to accommodate all dimensions in the three coordinate planes that prescribe the locations of the different elements and, in turn, the retroreflective geometry of a specific road sign situation. The program then computes the defined angles determined by those inputs. (The complete mathematical analysis of the vector structure and the derivations of the defined angles by D. Couzin are available on request from the author.)

ERGO easily determines exact, not approximate, retroreflective geometry for any set of input data desired. Each set of correlates generated by this program is specific to the one corresponding set of input dimensions that exactly locate the eye, headlamps, and sign relative to each other. The values are absolute; the only subjectivity is in the selection of the input dimensions, or range of dimensions, to represent any generic designation such as typical STOP sign, large-offset guide sign, standard car, and so forth.

The parameters of location for car headlamps, driver's eye, and sign location that are inputs for ERGO are as follows (all input dimensions are entered in meters or, in an alternative menu choice, a version is available in which all inputs are in feet):

ROAD DISTANCE to Sign: _____
SIGN: Offset from Road Edge: _____
Height above Roadway: _____

VEHICLE DIMENSIONS (STANDARD CAR):	*Meters*	*Feet*
Separation between headlamps	1.042	3.42
Headlamp height over roadway	.661	2.17
Eye height over headlamps	.466	1.53
Eye setback behind headlamps	2.057	6.75
Eye displacement left of vehicle centerline	.330	1.08

Dimensions were measured for a wide variety of vehicles in many models. The dimensions above are the mean of a relatively narrow range of data for compact and mid-size cars and thus well represent the universe of such cars. These mean values have been dubbed the "standard car" and are included as default values in ERGO. Of course, any values can be entered to override the defaults. Separate dimensions were determined for such vehicle groups as large cars, small vans, large vans [recreational vehicles (RVs)], and large trucks with maximum eye-headlamp displacements, dubbed "MAX trucks."

OBSERVATION ANGLE: LABORATORY AND ROAD DEFINITIONS

An accurate understanding of the observation angle is critical both to understanding the effects of the different inputs on the geometry and to using the output data correctly. For laboratory test purposes, observation angle can be defined as follows:

> The angle that is formed at the reference center on the test sample between a line to the light source (the illumination axis) and a line to the receiver (observation axis) (see Figure 1a).

It is useful to observe that its measure is a function of the displacement distance from the light source to the receptor (measured perpendicular to the illumination axis) and the distance measured along the illumination axis. This is as defined (in slightly different terminology) in ASTM E808-91.

In the actual road situation where the driver of an approaching vehicle observes a road sign illuminated by the car's headlamps, determining the observation angle at which the sign is seen is a bit more complicated. In the literature, even as recently as the reports by Black et al. (*2*) and by McGee and Mace (*3*), the observation angle for the driver has consistently been presented as if it were simply the vertical displacement of the eye above the level of the headlamps. However, this is not correct.

Note that in Figure 2a (which diagrams the eye-headlamp relationships for the standard car), the vertical distance down from the eye is a dimension from the eye to nothing.

In truth, the observation angle, whether it is measured in the laboratory or on the road, is the angle intercepted (at the particular road or test distance) by the straight-line displacement of the receptor (or eye) from the light source illuminating the reflector sample or sign. In the road situation, the receptor is the human eye; the two eyes are sufficiently close together that they can be considered one point at the centerline of the driver. The light source is a headlamp.

Unfortunately for the cause of simplicity, (*a*) there are two headlamps, that is, two separate light sources illuminating signs; (*b*) the headlamps are unequally displaced on either

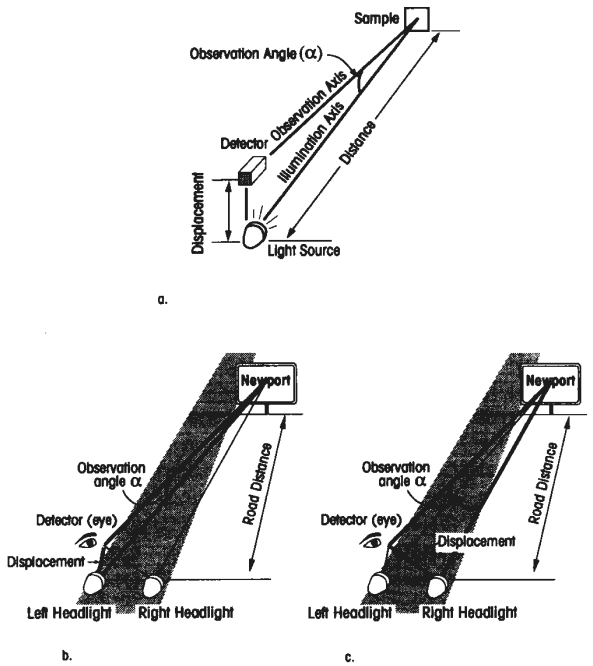
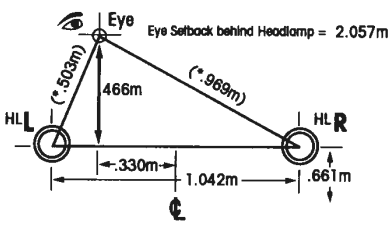


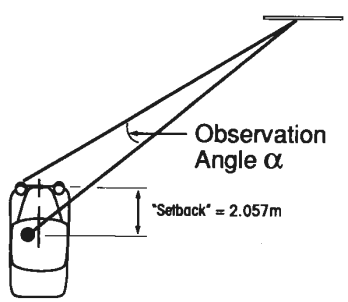
FIGURE 1 Observation angle: (*a*) laboratory test setup per specifications; (*b*) road to left headlamp; (*c*) road to right headlamp.



a.

*Not an ERGO input value but shown for the "Standard Car."

(1 meter = 3.28 ft.)



b.

FIGURE 2 Vehicle dimensions in ERGO (primarily affecting observation angle): (*a*) standard car dimensions; (*b*) setback dimension and effect on observation angle.

side of the driver; and (*c*) the headlamps are at a substantial separation. This means that in order to be accurate and mathematically specific, two different observation angles are in effect for each road sign situation. One is the angle intercepted by the displacement to the left (driver's side) headlamp and the other is the angle intercepted by the displacement to the right headlamp. [The necessity of computing the angles to each headlamp separately has also been recognized by Johnson (*4*).]

Figure 1b (to left headlamp) and Figure 1c (to right headlamp) illustrate how these two observation angles are formed between the respective headlamp, the eye, and the sign. Note the correspondence of the elements to the laboratory setup (Figure 1a).

Another factor, which appears to have often been overlooked, can also substantially complicate observation angle calculations under certain conditions. It is automatically included in ERGO's complete computation. This involves the setback distance. In all vehicles the eye is set back behind the headlamps by a substantial distance; the standard car setback averages 2.06 m (6.75 ft). For a driver viewing signs at very small offsets (off the road) and at substantial distance, the setback occurs more or less parallel to the observation axis and thus does not enter into the determination of the observation angle.

However, as a vehicle approaches close to a sign that is substantially offset to one side or the other, or as it turns away from the sign even slightly, as on a curved approach, the setback becomes an increasingly significant component of the eye-headlamp displacement that produces significantly larger observation angles. The rate of increase accelerates at very close distances, producing extremely large observation angles, sometimes even completely out of the effective range of retroreflected light. The principle is illustrated in Figure 2b.

APPLYING ERGO DATA AND DATA SUMMARY GRAPHS

Analysis of data from ERGO can yield substantial information on how retroreflective signs are actually seen. It can be used to determine which observation and entrance angles should be specified for any particular application. As a part of studies of the parameters of effectiveness of signs—legibility distance, detection distance, and so on—it can be useful in indicating where effective retroreflectivity is required, namely, at the observation angle that corresponds to some determined distance having an important function.

The few graphs summarizing ERGO-derived data shown here illustrate how some useful principles can be deduced. Following are a few guidelines for interpreting the ERGO data presented here.

First, plots of angular data can apply to many different sizes and types of signs if the signs are mounted at offsets and heights similar to those shown. However, the point at which a particular sign is usefully seen or detected may not start or end at the endpoints of the plot shown on a given graph. The beginning and end of the useful viewing time for a sign must be independently determined and then the angles corresponding to those distances should be noted.

In using ERGO to evaluate the performance of a given material for a particular type of sign, certain criteria should be separately evaluated: (*a*) the distance at which a particular sign needs to be detected, (*b*) the distance at which it should be read, (*c*) the span of distance during which it continues to be usefully read (and thus also the reading "time" based on a given approach speed), and (*d*) the distance between the approaching driver and the sign when the driver can no longer be expected to read the sign or no longer needs the information. Then, using ERGO, the observation and entrance angle correlates should be noted for those various determined distances.

In the opinion of this author, a determination should also be made in using the above series of data points, although its evaluation is not strictly a part of geometry-limited ERGO. It applies to reflectivity values (and luminance data, if available) at the "far" and "near" limits, especially in the selection between materials of different characteristics. This determination is whether the sign luminance at the far distance limit is less than, more than, or equally as important as that at the near distance limit (at which the sign viewing is actually terminated). Note that the near distance limit is reached after the sign has been observed and read during the entire span of time after the initial reading until reaching the near limit.

ERGO DATA OUTPUTS

The ERGO program output provides values for all the defined angles of retroreflectivity that the input values determine. An example of the actual output for a single road sign situation as reported by ERGO is shown below:

	Left Headlight	*Right Headlight*
Alpha (α)	0.33	0.52
Beta (β)	2.97	2.42
Gamma (γ)	39.29	121.09
Epsilon (ε)	29.98	−56.89
Omega (ω)	69.24	64.23
Beta 1	2.30	−1.25
Beta 2	1.88	2.07
Beta V	1.05	1.05
Beta H	2.78	2.18

In this example, the inputs defined a point on a sign that is offset 2.5 m (8.2 ft) from the edge of the road at a height of 2.5 m (8.2 ft) viewed from the standard car at a road distance of 100 m (328 ft). Output values of ERGO are given for the geometric parameters, which are defined for the laboratory test setup by ASTM E808-91. Two other parameters have been created for the road situation only. The geometric parameters output by ERGO are as follows:

Alpha: Observation angle
Beta: Entrance angle
Gamma: Presentation angle
Epsilon: Rotation angle (ASTM E808-91)
Omega: Orientation angle (ASTM E808-91)
Beta 1: Entrance angle component as defined
Beta 2: Entrance angle component as defined

Apply to ROAD environment ONLY: (not ASTM, not prior CIE)

Beta V: Entrance angle vertical component
Beta H: Entrance angle horizontal component

The analyses in this paper are principally concerned with the observation and entrance angle values, but other values can be important to laboratory tests or specifications intended to correlate with actual road performance, or to both.

The ERGO data presented in the balance of this paper consist of the observation and entrance angle outputs for particular signs over a range of approach distances. These data present the range of these angles that actually occurs for given signs as seen by drivers of approaching vehicles. The data are presented in graphs that plot observation angle (on the vertical scale) against road distance (on the horizontal scale). Since road distance is linear, it is very important to note that the plot is also one of time, given a specific vehicle approach speed. Since the driver's information and decisions are primarily defined by time, this type of graph best represents the rate of change in observation angle as the observing vehicle approaches the sign. Shown below the graphed data is the time in seconds before the vehicle passes the sign at various distances and for speeds of 50 kph (30.1 mph), 75 kph (46.6 mph), and 100 kph (62.1 mph).

Of course, there is an entrance angle correlate for every observation angle in the data. In the lower right-hand corner of most of the graphs is a separate plot of entrance angle against the common horizontal road distance scale. The scale for increments of entrance angle is the short vertical scale along the lower right side of the graph. To avoid confusion with the observation angle plots, the entrance angle output is only plotted when it exceeds 5 degrees. This is acceptable because any entrance angle of 5 degrees or less is considered equivalent to zero degrees. In fact, sheeting is actually tested at 4 or 5 degrees to avoid front surface reflection. The entrance angle plots are short because entrance angle does not exceed 5 degrees until the approaching vehicle is very close to the sign.

An alternative type of graph would plot observation angle against entrance angle. Thus, that plot is the compilation of specific sets of correlates of observation and entrance angles. The correlates of any specification can also be shown as specific points. This type of graph provides the best comparison of specification test points with the actual geometry, especially for unusual or extreme situations.

Road distance can be marked on the actual plots on this second type of graph but it is very nonlinear, with increments of distance very compressed for the longest distances and then increasing to longer and longer spans as the vehicle approaches the sign.

ERGO DATA GRAPHS

Several graphs summarizing ERGO-produced data are shown. The examples were selected to demonstrate a variety of circumstances in which the data from this program can be useful. Analysis of the summarized and plotted data for particular signs can reveal important relationships between the angular

variables (primarily observation angle) and other variables (primarily road distance).

STOP Signs and All Near-Roadside Signs

STOP signs have very specifically defined locations, one component of which is very small offsets from the road edge. In Figure 3, the solid-line plots represent a minimal urban offset of 0.6 m (2 ft). The dashed-line plots represent a large rural offset of 3.65 m (12 ft). The majority of right-edge roadside signs are located within this range.

The plots, virtually identical for either offset, demonstrate that this difference in offsets has essentially no effect on the observation angle value. The data also show that the mean entrance angle is only 13 degrees, even for the larger offset when the approach distance is only 25 m (82 ft) and the mean observation angle is 2.2 degrees.

Zwahlen (*5*) has shown that drivers approaching a STOP sign looked away from their final viewing ("last look") of the STOP sign at a mean distance of 47.6 m (156 ft) for the worst condition studied and this was after they had viewed the sign for 148 m (484 ft); presumably they no longer needed the information. Thus the effective distances for STOP signs involve observation angles of 1 to 0.5 degrees and entrance angles of 10 degrees or less.

Overhead Sign

Figure 4 is the plot for an overhead sign centered over the driver's lane at a height of 7 m (23 ft). Overhead signs are mounted at a very limited range of locations relative to the driving lane, which requires them to be considered a significant and separate category. They are always designed to be read at significant distances, and their fixed position above observing vehicles and perpendicular to the vehicles' direction determines that the observation and entrance angles differ very little from site to site. Assuming initial detection in the range of 200 to 300 m (656 to 984 ft) for a very significant span of time after initial detection and viewing, the observation angle in effect for the approaching driver is very small; the entrance angle is negligible. More than any other type, this sign functions during its useful viewing distance at very

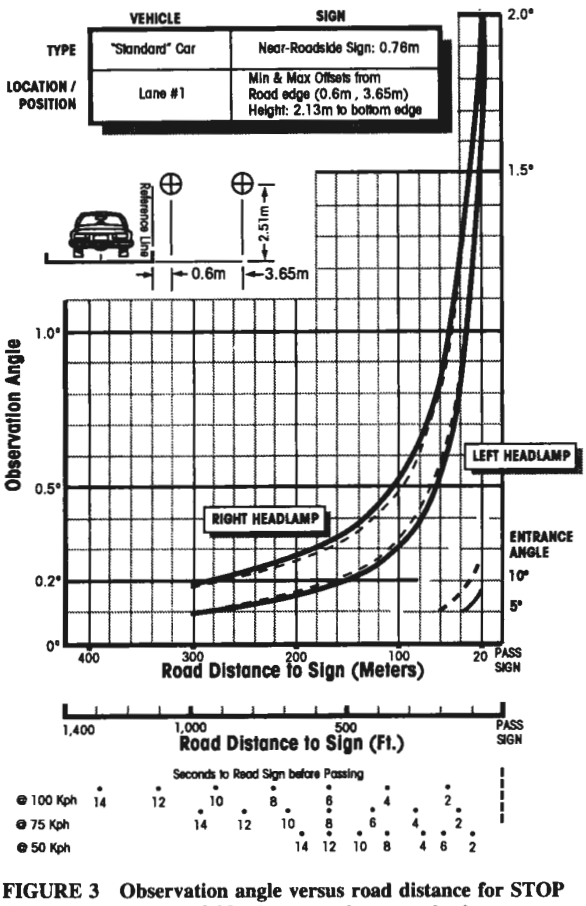


FIGURE 3 Observation angle versus road distance for STOP signs and all near-roadside signs, regulatory and other. Entrance angle shown where 5 degrees or more (to lower right vertical scale).

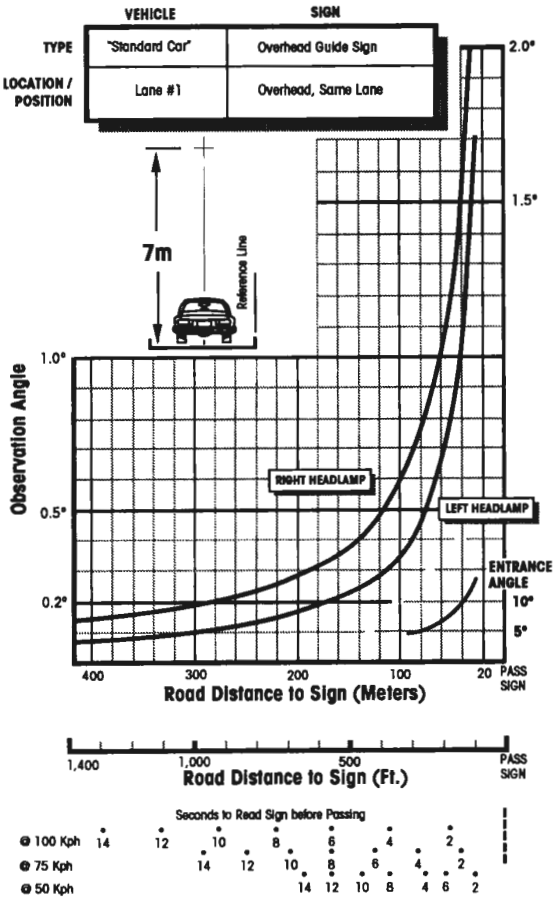


FIGURE 4 Observation angle versus road distance for overhead guide signs. Entrance angle shown where 5 degrees or more (to lower right vertical scale).

small observation and entrance angles. As close as 30 m (98 ft), where the observation angles are about 1.5 degrees and the driver has probably terminated viewing of the sign, the entrance angle is still only 13 degrees.

Large-Offset Signs

Figure 5 shows the observation and entrance angle correlates both to the center of a very wide sign [5.5 m (18 ft)] and at a very large offset from the road edge [9.1 m (30 ft)]. Thus the entrance angle computations are to a point offset 14.6 m (48 ft) from the road edge at a height of 3.34 m (11 ft). Note that for signs at such a large offset, the observation angle curves for left and right headlamps cross over as the line of sight passes over the right headlamp when the vehicle is close to the sign.

Comparison of Vehicles with Different Eye-Headlamp Displacements

Figure 6 is a comparison of the differing observation angles at which drivers of certain types of vehicles with different eye-headlamp displacements view typical road signs at successive approach distances. The vehicles represented are as follows:

1. "Standard car" represents the mean dimensions of the compact, mid-size, and medium cars. The majority of cars fit well into this category.
2. "Large car" represents the mean dimensions of cars such as the Lincoln Town Car, the Chevrolet Caprice (mid-1980s style), and similar cars. Cars in this category are rapidly disappearing.
3. Large vans (RVs).
4. "MAX truck" represents the approximate dimensions of the largest truck-tractors with a maximum eye height of about 2 m (6.6 ft) above the headlamps.

Actually, of course, there is a continous range of trucks having various eye-headlamp displacements so as to create a continuum of plots of observation angle from that shown for large vans to that shown for the MAX truck.

[Note: To avoid having to present excessive data on one graph, only the observation angle data for the left headlamp are shown. The sign position used for the ERGO computations is offset from the road edge by 6.08 m (20 ft) and at a height of 2.13 m (7 ft). Changes in vehicle parameters have no effect on the entrance angle; therefore no entrance angle data are shown.]

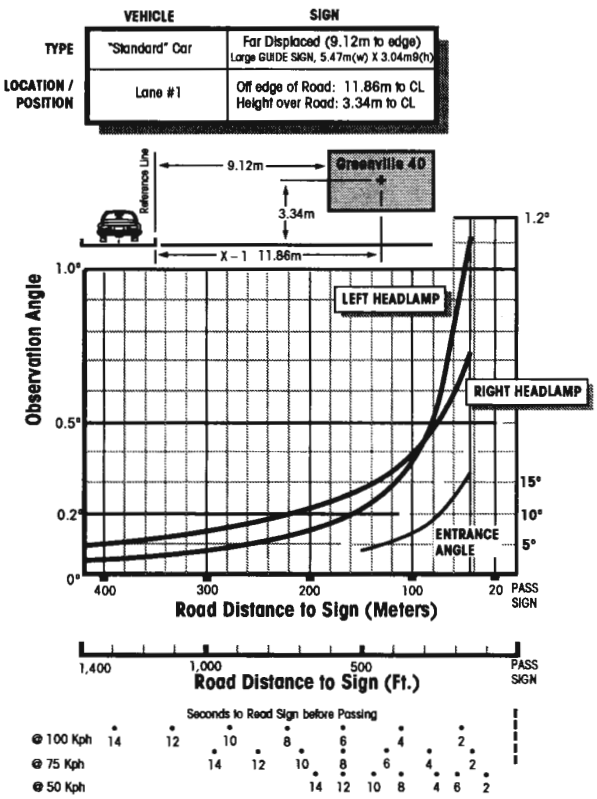


FIGURE 5 Observation angle versus road distance for signs at large offset from highway. Entrance angle shown where 5 degrees or more (to lower right vertical scale).

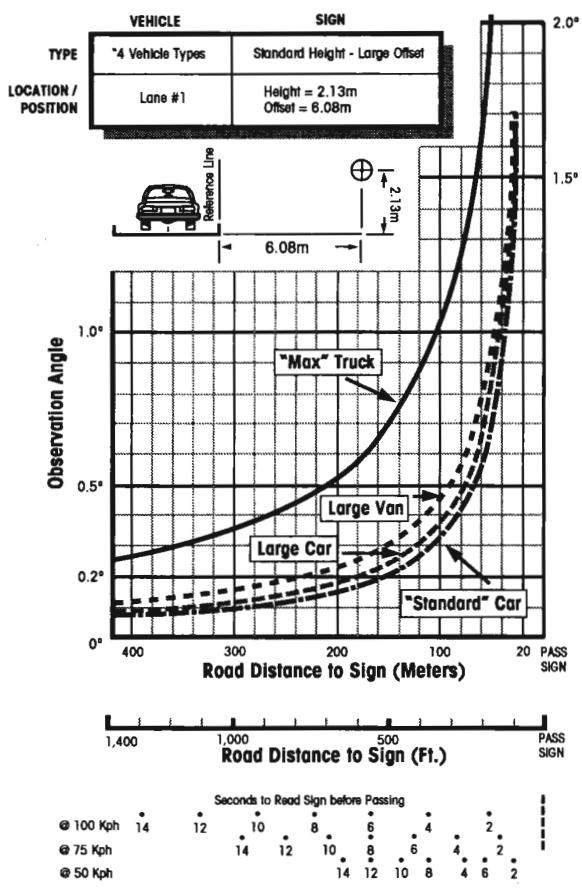


FIGURE 6 Observation angle versus road distance from different vehicles (left headlamp only) to same sign; right side, 2.13 m high.

RETROREFLECTIVE SIGNS: EFFECTIVE PERFORMANCE PRINCIPLES

Some significant principles relating to the effective performance of retroreflective sheeting on road signs can be noted in or deduced from ERGO data. The data developed in ERGO can also be a valuable addition to other experimental data and observations in correlating particular charateristics of reflective sheeting performance with the effectiveness of road signs at night. The four ERGO graphs relating to the geometry of signs (Figures 3–6) apply to and demonstrate the points discussed below. The graphed data are from ERGO calculations.

The most important determinant in the performance of retroreflective sheeting materials for any given application is the direct (although nonlinear) relationship of observation angle and road distance:

1. A specific observation angle value equals a specific road distance (for a given vehicle).
2. Observation angle increases as road distance decreases.

As shown on the three plots of ERGO data for different signs (Figures 3–5), the observation angle is very small (about 0.1 degree) when the road distance is as long as 280 m (919 ft) or more. As the vehicle approaches the sign from a great distance, the observation angle changes very slowly. Depending on the vehicle speed and the size of the sign, the approaching driver may see the sign for 10 sec at 0.1-degree observation angle. The observation angle begins to change more quickly as the driver passes 0.2 degree at 156 m (512 ft) to the sign. If the rate of travel is 75 kph, only 3 sec will elapse before the driver reaches 69 m to the sign and a 0.5-degree observation angle. Now the angle is changing rapidly: in only 1.5 sec the driver is at a 1.0-degree observation angle and in 0.8 sec at a 2.0-degree observation angle. ERGO computations show that at 2.0 degrees nominal, the driver passes through 1.3 degrees of observation angle in 0.5 sec (1.5 to 2.8 degrees).

Table 1 gives carefully computed road distance values corresponding (exactly, for the left headlamp) to the specific observation angle test points of various specifications. Also shown is the time before passing the sign and the time before the next given test point. The data are computed for geometry to a point on a sign offset at 2.5 m (8.2 ft) and at a height of 2.5 m (8.2 ft) viewed from the standard car.

TABLE 1 Observation Angle Nominal Points (Exact for Left Headlamp) Versus Road Distance and Travel Time at 75 kph

Observation Angle Specification Points (degrees)	Distance from Sign (m)	Time Before Passing[a] (sec)	Distance and Time to the Next Observation Angle	
			Distance (m)	Time[a] (sec)
0.1	306	14.6	148	7.1
0.2	156	7.5	57	2.7
0.333	99	5	30	1.4
0.5	69	3.3	30	1.5
1.0	38.7	1.8	10.5	0.5
1.5	28.2	1.3	5.5	0.3
2.0	22.6	1.1		

[a]At 75 kph.

The purpose of the summary in Table 1 is to provide an easy reference for the sign distances that correspond to particular observation angle test points. The left headlamp is used because it is generally the primary source, the observation angle for the right headlamp being generally larger. Table 1 is applicable to virtually all sign displacements (both offset and height).

All the plots of observation angle versus road distance (Figures 3–6) display this reality: observation angle is a direct function of road distance. Since the displacement distance from a headlamp to the eye is relatively fixed until approach distances quite close to the sign are encountered, the relationship is direct and occurs within a very narrow range for all cars and even for small trucks. In other words, a specific observation angle defines a specific distance to a sign. It follows that studies attempting to accurately correlate distance with some measure of actual sign performance (detection, legibility, etc.) for any or for several retroreflective materials and to draw conclusions from their data must recognize this relationship: different road distances involve different observation angles. For example, an R-value at 0.2 degree cannot correlate with performance at 60 m (197 ft), since at that distance the observation angle is about 0.6 degree. Review of test data (*6*) for different materials reveals that the relationship between materials at 0.2 degree is substantially different from the relationship between them at 0.6 degree. The objective of arriving at valid conclusions from these studies requires taking into account the actual observation angles that occur on the road as revealed by ERGO. The effective application of this method would require having reflectivity (R_A) data at all observation angles, that is, an observation angle curve (0.1 to 2.0 degrees at least).

Therefore, it would also follow that different retroreflective materials cannot be accurately characterized or referenced by a single R_A-value, as if the reflected light was an amorphous, uniform blob centered around the light source. This implies that the ratios between these single-number values hold for all road distances. However, test data studied (Stimsonite photometric laboratory data, 1992, unpublished) demonstrate that Material A can be substantially lower than Material B in its 0.2-degree observation angle laboratory values but nevertheless produces higher sign luminance than Material B at certain distances (*7*). Nevertheless, the use of single values is quite common in characterizing the relative retroreflectivity of materials.

Reflectivity values at the very small observation angles correspond to the longer distances and thus determine initial detection and overall reading time for most signs. Equal sign luminance is not equally important at all road viewing distances. In order to provide adequate reading time and so forth, which includes all the considerations that are used to select the size of a sign and its legend for daytime viewing, the distance at which initial detection and subsequent "primary" reading of a sign occur is the most important distance to see a sign, day or night. This distance involves correlates of very small observation and entrance angles. Subsequent continued reading as the driver approaches close to the sign at large observation angles must be, in the author's opinion, far less "necessary." Note the distances given by Zwahlen at which drivers no longer looked at the signs.

In addition to the common angles (observation and entrance angles), which have been emphasized in the data derived from ERGO and presented in this paper, ERGO data can also demonstrate what changes do or do not actually occur for the other angles of retroreflective geometry at different distances for a variety of sign locations. These other angular parameters also have an effect on the effective R_A-value and on actual road performance. ERGO data collected for this study for signs at various locations show that if a given material that is rotationally nonuniform is mounted with a uniform predetermined material orientation for all signs, it will simply result in maximum performance of the material at some sign locations and minimal performance at others. True orientation values range from -90 degrees to +90 degrees for actual signs.

CONCLUSIONS

The ERGO program data developed by users in support of their study requirements can contribute to the knowledge of the characteristics of effective performance of retroreflective sheeting on road signs. Since the values are absolute, they can contribute to valid conclusions from data relating study variables and retroreflectivity. Thus, soundly based and accurate data can replace blanket applications of simplistic beliefs about what geometries fully characterize the effective performance of retroreflective sheeting for road signs.

ERGO can be applied by users to any road viewing situation and any viewing distance. Successive increments of selected variables can be entered, the output geometry determined, and the resultant change in the correlates of observation and entrance angle can be evaluated. To that data, R-values resulting from laboratory tests at exactly the sign correlates given by ERGO can be added for a more accurate comparison of different retroreflective materials.

It is hoped that ERGO will be useful to those studying the application of retroreflective materials and that it will contribute to the accurate use of retroreflectivity data with other visibility parameters to promote the development of accurate and valid conclusions.

The ERGO program, including the complete mathematical basis, will be made available to all interested parties studying retroreflectivity. Requests should be sent to the author.

ACKNOWLEDGMENTS

The author wishes to acknowledge the support of the Stimsonite Corporation in the development of the ERGO program. He particularly wants to acknowledge the work of Dennis Couzin, an independent consultant, who was solely responsible for the mathematical basis of ERGO and was invaluable in helping to determine the effects of the various defined geometric parameters. He is also grateful to Craig Heinze, who converted the mathematical formulas into a workable program.

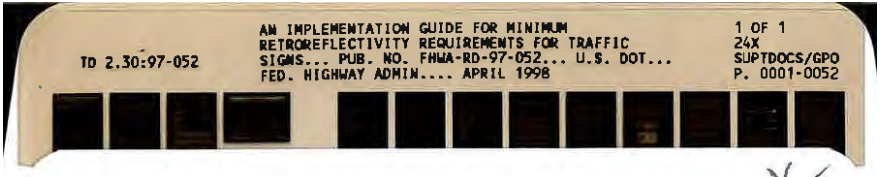
REFERENCES

1. *Instrumental Photometric Measurements of Retroreflective Material and Retroreflective Devices.* Federal Test Method 370. General Services Administration, March 1977.
2. Black, K. L., et al. *NCHRP Report 346: Implementation Strategies for Sign Reflectivity Standards.* TRB, National Research Council, Washington, D.C., 1992.
3. McGee, H. W., and D. L. Mace. *Retroreflectivity of Roadway Signs for Adequate Visibility: A Guide.* Report FHWA/DF-88/001. FHWA, U.S. Department of Transportation, 1987.
4. Johnson, N. L. Measuring the Appearance of Retroreflectors by Application-Oriented Goniophotometry. In *Review and Evaluation of Appearance: Methods and Techniques,* ASTM STP-914, Philadelphia, Pa., pp. 49–61.
5. Zwahlen, H. T. Stop Ahead Signs and Their Effect on Driver Eye Scanning and Driving Performance. In *Transportation Research Record 1168,* TRB, National Research Council, Washington, D.C., 1988, pp. 16–24.
6. Woltman, H. L., and T. J. Szczech. Sign Luminance as a Methodology for Matching Driver Needs, Roadway Variables, and Signing Materials. In *Transportation Research Record 1213,* TRB, National Research Council, Washington, D.C., 1989, pp. 21–26.
7. Zwahlen, H. T., Q. Li, and J. Yu. Luminance Measurements of Retroreflective Warning Signs Under Lowbeam and Highbeam Illumination at Night Using the CapCalc System. In *Transportation Research Record 1316,* TRB, National Research Council, Washington, D.C., 1991, pp. 31–38.

The contents of this paper represent the views and findings of the author, who is solely responsible for the opinions and conclusions presented here. The contents do not necessarily reflect the official views or policies of the Stimsonite Corporation.

Publication of this paper sponsored by Committee on Visibility.

APPENDIX E



UW-MADISON
WENDT LIBRARY
JUL 20 1998
U.S. DEPOSITORY COPY
DO NOT DISCARD

89073305922

b89073305922a

MAY 13 1998

0982-G-11 TD 2.30:97-052

An Implementation Guide for Minimum Retroreflectivity Requirements for Traffic Signs

PUBLICATION NO. FHWA-RD-97-052 APRIL 1998

98-021190

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

COMPLETED

FOREWORD

This report presents information aimed at providing guidance to agencies on all level on how they can cost-effectively meet the minimum maintained retroreflectivity guidelines for traffic signs while maintaining the signs on their highways. Over time, traffic signs deteriorate, losing their retroreflective properties and color. Eventually, the sign may be rendered undetectable and illegible, which could possibly create an unsafe driving environment. This report presents information essential for maintaing a system of highway signing that will serve the driving population in the most efficient manner possible.

Sufficient copies of the report are being distributed by FHWA to provide a minimum of two copies to each FHWA regional and division office, and five copies to each State highway agency. Direct distribution is being made to division offices.

A. George Ostensen
Director, Office of Safety and
Traffic Operations Research
and Development

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for the contents or the use thereof. The report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturers' names appear in this report only because they are considered essential to the object of the document.

Technical Report Documentation Page

1. Report No. FHWA-RD-97-052	2. Government Accession No.	3. Recipients Catalog No.
4. Title and Subtitle AN IMPLEMENTATION GUIDE FOR MINIMUM RETROREFLECTIVITY REQUIREMENTS FOR TRAFFIC SIGNS		5. Report Date April 1998 6. Performing Organization Code
7. Author(s) Hugh W. McGee and Jeffrey A. Paniati		8. Performing Organization Report No.
9. Performing Organization Name and Address Bellomo-McGee, Inc. (BMI) 8330 Boone Boulevard, Suite 700 Vienna, Virginia 22182		10. Work Unit No.(TRAIS) 3A1a0302 11. Contract or Grant No. DTFH61-93-C-00131
12. Sponsoring Agency Name and Address Office of Safety and Traffic Operations R&D Federal Highway Administration 6300 Georgetown Pike McLean, Virginia 22101-2296		13. Type of Report and Period Covered Final Report Sep. 1993 - Oct. 1996 14. Sponsoring Agency

15. Supplementary Notes
Contracting Officer's Technical Representatives:
Jeffrey Paniati, HSR-20
Douglas Lockett, HTA-30

16. Abstract

Although the *Manual on Uniform Traffic Control Devices for Streets and Highways* stipulates that all warning and regulatory signs be illuminated or reflectorized to show the same color and shape by day or night, there are no specific guidelines for required retroreflectivity levels. Therefore, the FHWA embarked on a comprehensive research program which resulted in recommended guidelines for minimum retroreflectivity values for four types of signs: yellow or orange warning signs, white on red regulatory signs, white regulatory signs, and white on green guide signs. The retroreflectivity values developed for each group of signs are considered the retroreflectivity levels below which the sign would be inadequate for meeting the nighttime visibility requirements for most drivers, and therefore, should be programmed for replacement.

To assist agencies in developing a cost-effective program for timely replacement of ineffective signs, this document was prepared. Initially the report describes the principles of retroreflectivity, the types of retroreflective materials, and the proposed minimum retroreflectivity guidelines. Then, the report presents the concept of a sign management system, and provides guidance for developing a sign inventory, conducting sign inspections, and maintaining signs. The report concludes with discussing options that State and local agencies can follow for replacing their ineffective signs and offers a minimum and desirable program.

17. Key Words	18. Distribution Statement		
Traffic signs, retroreflectivity, inventory, inspection, maintenance, replacement	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161		
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No of Pages 57	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

I

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

TABLE OF CONTENTS

BACKGROUND 1

PURPOSE OF THE GUIDE 2

PRINCIPLES OF RETROREFLECTIVITY 3

TYPES OF RETRORELECTIVE SHEETING MATERIALS 6

MINIMUM RETROREFLECTIVITY REQUIREMENTS 11

SIGN MANAGEMENT SYSTEM 15

SIGN INVENTORY 17

SIGN INSPECTION 31

SIGN MAINTENANCE 36

SIGN REPLACEMENT OPTIONS FOR MEETING MINIMUM RETROREFLECTIVITY LEVELS 39

MINIMUM RETROREFLECTIVITY IMPLEMENTATION GUIDELINES 43

APPENDIX A FHWA SIGN MANAGEMENT SYSTEM (SMS) SUMMARY DESCRIPTION 46

REFERENCES 50

LIST OF FIGURES

Figure No.

1. Types of retroreflectors 3
2. Illustration of entrance and observation angles under actual highway conditions ... 5
3. Physical composition of three types of retroreflective sheeting 7
4. Integrated traffic sign management system 16
5. FHWA sign management system 26
6. Example of an inventory program that includes sign picture 27
7. Sign inspection using model 920 retroreflectometer 35
8. Components of the model 920 retroreflectometer 35
9. Exterior view of FHWA's SMARTS 37
10. Interior view of FHWA's SMARTS 37

LIST OF TABLES

Table No.

1. **Minimum coefficient of retroreflection of Type I sheeting** 8

2. **Minimum coefficient of retroreflection of Type II sheeting** 8

3. **Minimum coefficient of retroreflection of Type III sheeting** 9

4. **Minimum coefficient of retroreflection of Type IV sheeting** 9

5. **Minimum coefficient of retroreflection of Type VII-A sheeting** 10

6. **Minimum coefficient of retroreflection R_A for Type VII-B sheeting** 11

7. **Minimum retroreflectivity guidelines for black-on-yellow and black-on-orange warning signs** 13

8. **Minimum retroreflectivity guidelines for black (and/or red)-on-white regulatory and guide signs** 14

9. **Minimum retroreflectivity guidelines for white-on-red regulatory signs** 14

10. **Minimum retroreflectivity guidelines for white-on-green guide signs** 15

11. **Core data elements** 23

12. **Critical data elements** 23

13. **Desirable data elements** 24

14. **Sign replacement options** 40

BACKGROUND

Traffic signing is a critical component of any road because it is the mediu.. by which the highway agency communicates with the users (motorists, bicyclists, and pedestrians), providing information related to regulations, warnings, and directional guidance. As stated in section 1A-2 of the *Manual on Uniform Traffic Control Devices (MUTCD)*, "To be effective, a traffic control device should meet five basic requirements:[1]

1. Fulfill a need.
2. Command attention.
3. Convey a clear, simple meaning.
4. Command respect of road users.
5. Give adequate time for proper response."

When applied to traffic signs, this means that among other requirements, the traffic signs must be detectable and legible at a sufficient distance commensurate with their purpose. The term detectable is used to mean that the sign, while not necessarily completely legible, can be seen or detected by the user from a prescribed distance. Legible means that the sign message, either words or symbols, can be read or recognized from a prescribed distance. The critical features of any sign must apply under both day and night conditions.

Traffic signs are designed to satisfy these visual requirements by meeting specifications for size of the sign, and in particular the size of the letters, numerals, and symbols; by the use of certain colors designated for type of message; and by the material used for the sign face. To ensure that the user can detect and read the sign during night conditions, retroreflective materials are commonly used.[1] These materials consist of one of several grades or types of retroreflective sheeting, containing either micro-sized beads or prisms, and/or retroreflective prismatic-type buttons. Principles of retroreflectivity are described later in this document.

Over time traffic signs can deteriorate in a number of ways, but the primary mechanism is the loss of retroreflectivity and the fading of the color portions. When the former condition occurs, the sign becomes undetectable and illegible at night unless illuminated by a light source at the sign. When the latter occurs, the sign will lose its distinguishing color, which for signs such as the STOP sign and other red background signs is critical, and will lose its contrast condition making it less detectable and legible, even during daytime.

When signs are not maintained to an adequate legibility level during both, day and night conditions, highway users will miss the message resulting in possible inconvenience, misdirection, and even accidents. Inadequate and poorly maintained signage is often cited as the

[1]A small percentage of signs may be internally illuminated, such as street name signs and intersection control signs, or externally illuminated, such as overhead guide signs on freeways. For the latter, the material for the legend, and, for most guide signs, the green background is typically retroreflective.

contributing factor to accidents and has been the primary factor in numerous tort liability claims across the country.

PURPOSE OF THE GUIDE

Given the importance of the retroreflectivity properties of a sign to meet motorists' detection and legibility needs, the Federal Highway Administration (FHWA) is considering issuing guidelines on the minimum level of retroreflectivity required for certain types of signs.[2] These minimum levels would be considered thresholds below which the sign would be considered inadequate and should be replaced.

With the issuance of and in support of the national guidelines, the FHWA is providing guidelines on how agencies of all levels could cost-effectively meet these minimum maintained retroreflectivity guidelines while maintaining traffic signs on their highways. The purpose of this guide is to document these guidelines.

Key to maintaining signs at an effective level is a sign management system, which, as will be explained, is a series of coordinated activities from sign acquisition and installation to eventual replacement. The level of sophistication of a sign management system will be dependent upon the needs, desires, and capabilities of the individual agency.

To assist the agencies in developing their sign management system and meeting the minimum retroreflectivity requirements, the following is presented in this guide:

- An explanation of the principles of retroreflectivity and minimum retroreflectivity requirements.
- Elements of a comprehensive Sign Management System.
- Procedures for establishing a sign inventory.
- Procedures for conducting sign inspections.
- Sign maintenance considerations.
- Options for implementing and meeting the minimum retroreflectivity requirements.

---

[2] Section 406(a) of the 1993 Department of Transportation Appropriation Act required the Secretary of Transportation to revise the MUTCD to include a standard for minimum level of retroreflectivity that must be maintained for traffic signals.

- Suggested minimum and desirable programs for meeting the minimum retroreflectivity requirements.

PRINCIPLES OF RETROREFLECTIVITY

Before describing minimum retroreflectivity requirements and how they can be met, a basic understanding of the principles of retroreflectivity is needed. The basic principle of retroreflection is that the light coming from a light source is returned or reflected back in the direction of the source. This is accomplished through the use of spherical reflectors (micro-sized glass beads) or cube-corner reflectors (micro-sized prisms) as illustrated in figure 1. The light source is typically the vehicle headlight, and candlepower, or its metric equivalent candela, is the unit of measurement for this light. The intensity of this light on the sign surface is known as **illuminance** and is measured in terms of foot-candles or lux in metric equivalent. The light that is returned to the observer near the light source is known as **luminance** and is mea_ ed as candelas per square foot or square meter. Luminance is, therefore, what the motorist actually sees when the vehicle headlights hit the sign.

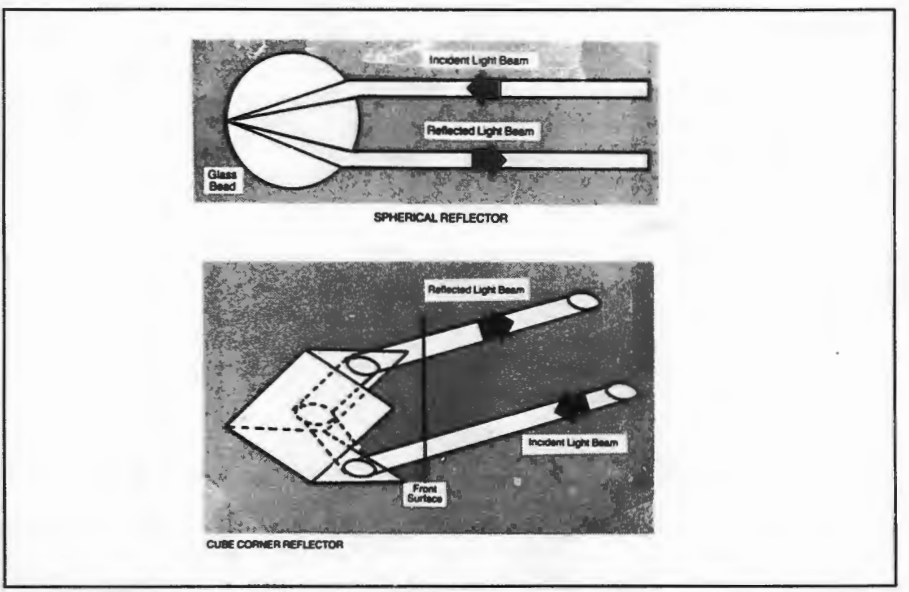


Figure 1. Types of retroreflectors.

Retroreflective materials are basically constructed with either micro-sized glass beads or prisms to provide their retroreflective properties. The principal feature that distinguishes various types of retroreflective materials is the coefficient of retroreflection (R_A). (The various types of retroreflective sheetings will be described in the next section.) This property is precisely defined in American Society for Testing and Materials (ASTM) "E 808 Practice for Describing Retroreflection", but basically it can be defined as the amount of light (i.e., luminance measured as candelas per square foot or square meters) that comes out from the retroreflective material per amount of light coming in from the light source, i.e., the vehicle headlights (i.e., illuminance measured as foot-candels or lux).[(2)3] The R_A value is expressed as candelas per foot candle per square foot ($cd/fc/ft^2$) in English or candelas per lux per square meter ($cd/lx/m^2$) in metric measurements. The higher the R_A value, the brighter the material appears to the motorist.

The retroreflectance of sheeting materials is always described in context of an important property, its angularity, which is defined by the entrance (of the light) and the observation (by the motorist) angles. These two angles are depicted in figure 2 for a roadside, post-mounted sign and an overhead sign. The entrance (or incidence) angle is the angle formed between a light beam striking the surface of a sign and a line coming out perpendicular from the surface. The observation angle is the angle between the incoming light beam and the reflected light beam as it is seen by the motorist. These angles change with distance between the vehicle and the sign, and are a function of the location of the sign and the vehicle (for the entrance angle) and the height of the driver's eye with respect to the vehicle headlamps (for the observation angle).

While the R_A is sensitive to changes in both the observation and entrance angles, it is much less sensitive to the entrance angle, except at large angles. For ASTM Type I, II, and III retroreflective sheeting materials substantial change in R_A does not occur at entrance angles less than 20 degrees and for some materials significant change does not begin until the entrance angle exceeds 30 degrees.

Unlike the case of the entrance angle, even the slightest change in the observation angle can have dramatic effects on R_A. Since the distance between the driver's eye and the light source is fixed, every time the distance between the observer and the target sign is doubled, the observation angle is cut in half. Due to its high degree of sensitivity, the observation angle plays the most important role in the calculation of R_A.

The "angularity" of the sign refers then, to the range of angles at which a sign will remain retroreflective. An entrance angle of 30 degrees is considered wide for highway signing.

Since a retroreflective material is supposed to reflect all the light directly back to the source, ideally, the observation angle should be zero. However, in reality this is not the case since the

---

[3] The ASTM specifications discussed throughout this Guide are found in reference number 2, which is a compendium of standards related to color and appearance measurement.

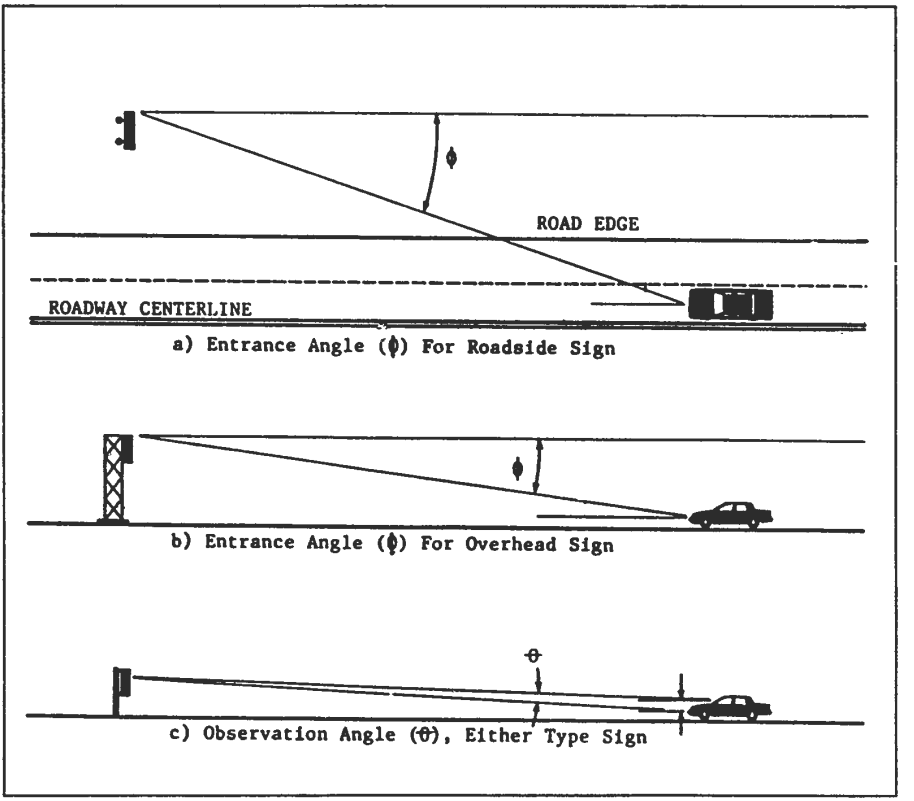


Figure 2. Illustration of entrance and observation angles under actual highway conditions.

driver's eye is higher than the vehicle headlight and can range from 21 in (0.5 m) for small cars to as much as 64 in (1.6 m) for large trucks. A wide observation angle is anything over 2 degrees.

Finally, the cone of reflected light refers to the spreading of the reflected light beam. A good retroreflector will have a very small cone, with most of the reflected light being within 3 degrees of the incoming light ray.

Minimum retroreflectance is prescribed at two observation angles, and two entrance angles and for each different type of sheeting of different colors. The two observation angles of +0.2 and +0.5 degrees equate to a viewing distance of 500 ft (152 m) and 200 ft (61 m), respectively

assuming that the driver height is 21 in (0.5 m) above the headlight. The two entrance angles are -4 and +30 degrees. The 30 degrees is considered to be the widest angle between the driver and any sign that would have to be seen. The -4 degrees is intended to be for signs close to the edge of the roadway but oriented away from the perpendicular to avoid the specular reflection that occurs at 0 degrees.

TYPES OF RETROREFLECTIVE SHEETING MATERIALS

The retroreflectivity of signs is accomplished by using either retroreflective sheeting for both the legend and the background or, in the case of some large guide signs, using retroreflective elements that are housed in white embossed aluminum frames cut in the shape of letters, symbols and borders. This so-called "button copy" is then attached (riveted) to retroreflective sheeting or non-retroreflective enamel-coated material. For the vast majority of roadside signs, retroreflective sheeting is used for both the background and the legend.

Over the years industry has developed different types of retroreflective sheeting materials using either a glass bead or a prism as a method for providing the retroreflective properties. As new products are developed the classification has changed and expanded to accommodate these materials. The most recent and most recognized classification of retroreflective sheeting material for traffic signs (and delineators which use retroreflective sheeting) is found in the ASTM Standard Specification for Retroreflective Sheeting for Traffic Control, D 4956-93. [2] Of the six classes identified in that specification, the following four relate to highway signing:

- Type I — A medium-intensity retroreflective sheeting referred to as "engineering grade" which is typically enclosed lens glass-bead sheeting.
- Type II — A medium-intensity retroreflective sheeting sometimes referred to as "super-engineering grade" which is typically enclosed lens glass-bead sheeting.
- Type III — A high-intensity retroreflective sheeting which is typically encapsulated glass-bead retroreflective material.
- Type IV — A high-intensity retroreflective sheeting which is typically a non-metallized microprismatic retroreflective element material.

One of the distinguishing features of these four types is their basic construction. Types I and II are enclosed lens type sheeting, type III is an encapsulated lens type sheeting, and type IV is a prismatic lens type sheeting. Their basic construction is depicted in figure 3.

The principal characteristic that distinguishes the various types of retroreflective sheeting is the coefficient of retroreflection, R_A, produced at different entrance and observation angles. Tables 1 through 4 provide the minimum R_A values for the four types listed above. The FHWA

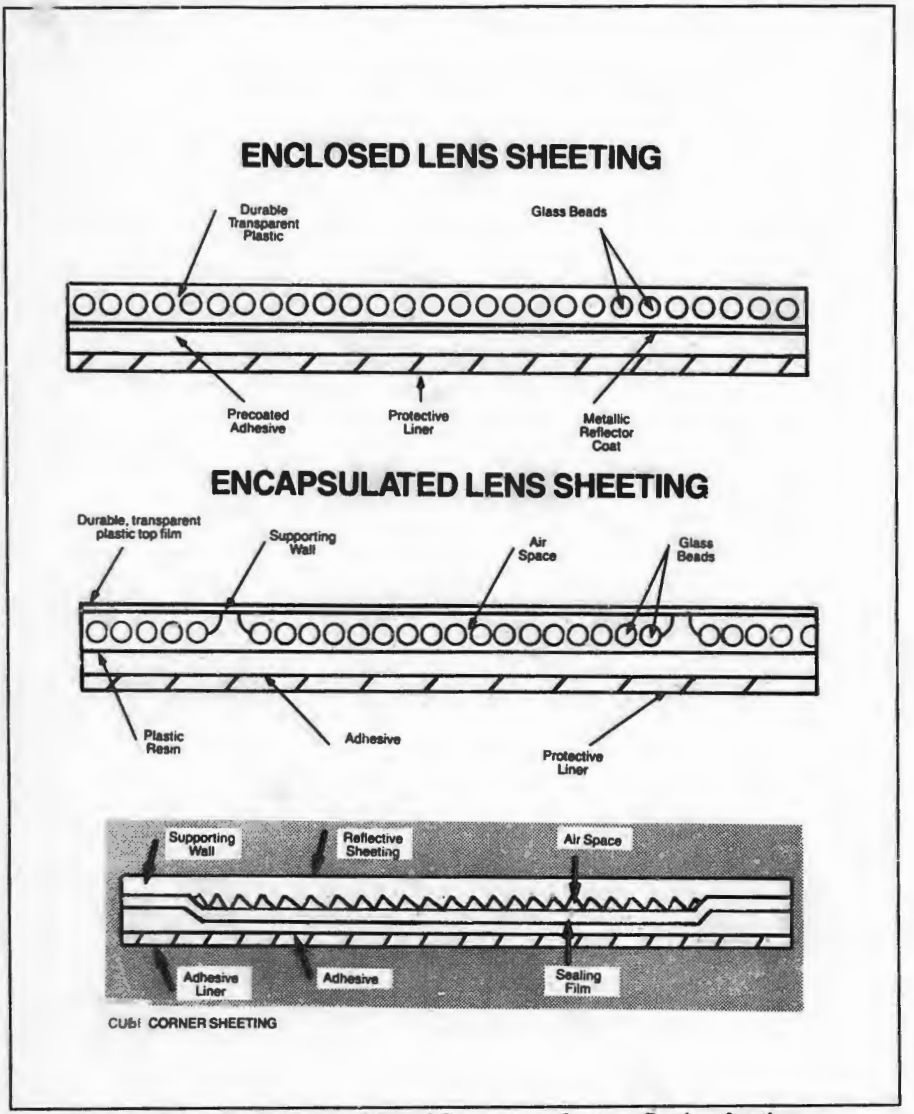


Figure 3. Physical composition of three types of retroreflective sheeting.

has adopted these specifications in their *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects, FP-96*, with one exception for type I brown sheeting, which is noted at the bottom of table 1.[3] Individual States have their own specifications which may differ slightly from the values shown in these tables.

Table 1. Minimum coefficient of retroreflection for Type I sheeting.

Observation Angle (Deg.)	Entrance Angle (Deg.)	Coefficient of Retroreflection[a]						
		White	Yellow	Orange	Green	Red	Blue	Brown[b]
0.2	-4	70	50	25	9.0	14.0	4.0	1.0
0.2	+30	30	22	7.0	3.5	6.0	1.7	0.3
0.5	-4	30	25	13	4.5	7.5	2.0	0.3
0.5	+30	15	13	4.0	2.2	3.0	0.8	0.2

[a] cd/fc/ft² (cd/lx/m²)
[b] FHWA FP-96 specifies 2 cd/fc/ft² at 0.2° observation angle and -4° entrance angle, 1.0 cd/fc/ft² at 0.2° observation angle and +30° entrance angle and at 0.5° observation angle and -4° entrance angle, and 0.5 cd/fc/ft² at 0.5° observation angle and +30° entrance angle

SOURCE: Refs. (2,3)

Table 2. Minimum coefficient of retroreflection for Type II sheeting.

Observation Angle (Deg.)	Entrance Angle (Deg.)	Coefficient of Retroreflection[a]						
		White	Yellow	Orange	Green	Red	Blue	Brown
0.2	-4	140	100	60	30	30	10	5
0.2	+30	60	36	22	10	12	4	2
0.5	-4	50	33	20	9	10	3	2
0.5	+30	28	20	12	6	6	2	1

[a] cd/fc/ft² (cd/lx/m²)

SOURCE: Refs. (2,3)

Another microprismatic material has been developed by at least one company which will likely be classified as Type VII. It has been identified as diamond grade material and has two types:

- Type A sheeting is wide angle retroreflective sheeting with optimized performance over a broad range of observation angles.

- Type B sheeting is wide angle retroreflective sheeting with optimized performance at narrow observation angles and with extended entrance angle performance.

Table 3. Minimum coefficient of retroreflection for Type III sheeting.

Observation Angle (Deg.)	Entrance Angle (Deg.)	Coefficient of Retroreflection[a]						
		White	Yellow	Orange	Green	Red	Blue	Brown
0.1[b]	-4	300	200	120	54	54	24	14
0.1[b]	+30	180	120	72	32	32	14	10
0.2	-4	250	170	100	45	45	20	12
0.2	+30	150	100	60	25	25	11	8.5
0.5	-4	95	62	30	15	15	7.5	5
0.5	+30	65	45	25	10	10	5	3.5

[a] cd/fc/ft² (cd/lx/M²)
[b] Values for 0.1° observation angle are supplementary requirements that shall apply only when specified by the purchaser in the contract or order.

SOURCE: Refs. (2,3)

Table 4. Minimum coefficient of retroreflection for Type IV sheeting.

Observation Angle (Deg.)	Entrance Angle (Deg.)	Coefficient of Retroreflection[a]						
		White	Yellow	Orange	Green	Red	Blue	Brown
0.1[b]	-4	400	270	160	56	56	32	12
0.1[b]	+30	120	75	48	13	13	7	3
0.2	-4	250	170	100	35	35	20	7
0.2	+30	80	54	34	9	9	5	2
0.5	-4	135	100	64	17	17	10	4
0.5	+30	55	37	22	6.5	6.5	3.5	1.4

[a] cd/fc/ft² (cd/lx/m²)
[b] Values for 0.1° observation angle are supplementary requirements that shall apply only when specified by the purchaser in the contract or order.

SOURCE: Refs. (2,3)

Tables 5 and 6 provide the R_A values for these two types as provided by its manufacturer.

It is emphasized that the R_A values found in tables 1 through 6 are for distinguishing the various types and are minimum values for new material. R_A values for newly purchased sheeting are often times higher than the minimum values for each of the types. However these R_A values are ore not what the driver necessarily needs for adequate detection and recognition of the sign at night. While in general, "brighter is better" especially, when signs need to be conspicuous among competing and distracting light sources at night, in many situations most drivers require a minimum level in order to discern the sign at a sufficient distance. The retroreflectivity values that are needed by the driver, and which, therefore, should be provided as a minimum are discussed next.

Table 5. Minimum coefficient of retroreflection for proposed type VII-A sheeting.

Observation Angle (Deg.)	Entranc Angle (Deg.)	Coefficient of Retroreflection[a]			
		White	Yellow	Blue	Green
0.20	-4	430	350	20	45
0.33	-4	300	250	15	33
0.50	-4	250	200	10	25
1.00	-4	80	65	4	10
0.20	30	235	190	11	24
0.33	30	150	130	7	18
0.50	30	170	140	7	19
1.00	30	50	40	2.5	5
0.20	40	150	125	6	15
0.33	40	85	75	4	8
0.50	40	35	30	1.5	3.5
1.00	40	20	17	0.7	2

[a] cd/fc/ft^2 (cd/lx/m^2)

Source: 3M Company
Note: This table contains non-proprietary information

Table 6. Minimum coefficient of retroreflection for proposed type VII-B sheeting.

Observation Angle (Deg.)	Entrance Angle (Deg.)	Coefficient of Retroreflection[a]			
		White	Yellow	Blue	Green
0.20	-4	800	660	215	80
0.20	30	400	340	100	85
0.20	45	145	85	25	12
0.20	60	35	23	6.6	2
0.50	-4	200	160	45	20
0.50	30	100	85	26	10
0.50	45	75	60	17	6
0.50	60	30	20	6.4	2

[a] cd/fc/ft^2 (cd/lx/m^2)

Source: 3M Company
Note: This table contains non-proprietary information

MINIMUM RETROREFLECTIVITY REQUIREMENTS

In anticipation of a national guideline on minimum maintained retroreflectivity level, i.e. R_A, the FHWA has sponsored research to determine what levels of sign retroreflectivity are needed by the road user. The results of that research led to the development of recommended minimum retroreflectivity levels below which signs would not provide adequate brightness for motorists' needs.[4] Minimum maintained retroreflectivity R_A values were developed for four groups of signs:

- Black message on yellow or orange background warning signs.
- Black and/or black and red message on white background regulatory signs.
- White message on red background regulatory signs.
- White message on green background guide signs.

The values that were presented in the research report were subsequently revised and are shown in tables 7 through 10.[4] These values are based on the standard of 0.2° observation angle and -4° entrance angle. The values presented in the four tables are based on:

(1) The results from research that utilized a human factors and mathematical modeling approach to consider the wide range of visual, cognitive, and psychomotor

capabilities of the driving population and the complexity of the relationships between the driver, the vehicle, the roadway environment, and the sign.

(2) The results from human factors research to evaluate the percent of drivers that would be accommodated by signs with varying levels of retroreflectivity.

(3) The results from measurements made on over 20,000 inservice signs in over 50 State and local jurisdictions.

(4) Input received from the more than 40 State and local jurisdictions represented at three regional workshops held in Baltimore, MD, Kansas City, MO, and Denver, CO in late 1995.

(5) Input from public agency and private industry representatives received at numerous presentations given at such forums as the Transportation Research Board (TRB) Annual Meeting, the Institute of Transportation Engineers Annual Meeting, the American Traffic Safety Services Annual Meeting, the TRB Visibility Symposium, and State-sponsored Safety and Traffic Engineering Workshops.

The recommended values only apply to yellow and orange warning signs, white and red regulatory signs, and green guide signs (excluding street name signs). They do not apply to parking signs, or brown or blue series signs. Given the many unresolved issues with vehicle headlamp performance specifications and the difficulty in measuring overhead sign retroreflectivity, at this time the FHWA is not recommending that minimum values be established for overhead-mounted signs.

In developing the recommended values, FHWA attempted to balance the desire to accommodate the highest percentage of drivers as practical with considerations of the budgetary constraints facing State and local jurisdictions. These values were developed in recognition of the fact that retroreflectivity is only one factor that contributes to poor nighttime performance of signs.

It should also be recognized that these values provide a guide as to the levels at which signs will become dysfunctional for a significant portion of the driving population under certain driving conditions. This does not mean that they will be dysfunctional for all drivers under all conditions. Signs with retroreflectivity values below these levels should be considered for replacement. These values should be used in connection with sound engineering judgement to determine the motorist's needs at a particular sign installation. Unique geometric situations or areas with complex visual backgrounds may require higher levels of retroreflectivity and/or larger or supplemental signs to provide the motorist with sufficient visibility for sign detection and recognition.

Table 7. Minimum retroreflectivity guidelines for black-on-yellow and black-on-orange warning signs.

Legend Color: Black
Background Color: Yellow or Orange

	Sign Size:	>=48-in	36-in	<=30-in
Legend	Material Type			
Bold Symbol*	ALL	15	20	25
Fine Symbol & Word	I	20	30	35
	II	25	35	45
	III	30	45	55
	IV & VII	40	60	70

All table values in cd/lx/m²
1 in = 2.54 cm

* Warning signs with bold symbols:

MUTCD Code	Sign Type	MUTCD Code	Sign Type
W1-1	Turn	W3-1a	Stop Ahead
W1-2	Curve	W3-2a	Yield Ahead
W1-3	Reverse Turn	W3-3	Signal Ahead
W1-4	Reverse Curve	W4-1	Merge
W1-5	Winding Road	W4-2	Lane Reduction
W1-6	Large Arrow	W4-3	Added Lane
W1-7	Double Head Arrow	W6-1	Divided Highway Begins
W1-8	Chevron	W6-2	Divided Highway Ends
W2-1	Cross Road	W6-3	Two-Way Traffic
W2-2	Side Road	W8-5	Slippery When Wet
W2-4	T Intersection	W11-2	Advance Pedestrian Crossing
W2-5	Y Intersection	W11A-2	Pedestrian Crossing
W20-7a	Flagger Ahead		

Source: FHWA

Table 8. Minimum retroreflectivity guidelines for black (and/or red)-on-white regulatory and guide signs.

Legend Color: Black and/or Black and Red
Background Color: White

Traffic	45 mi/h or greater			40 mi/h or less		
Sign Size:	>=48-in	30-36-in	<=24-in	>=48-in	30-36-in	<=24-in
Material						
I	25	35	45	20	25	30
II	30	45	55	25	30	35
III	40	55	70	30	40	45
IV & VII	50	70	90	40	50	60

All table values in cd/lx/m²
1 mi/h = 1.6 km/h
1 in = 2.54 cm

Source: FHWA

Table 9. Minimum retroreflectivity guidelines for white-on-red regulatory signs.

Legend Color: White
Background Color: Red

Traffic Speed:	45 mi/h or greater						40 mi/h or less					
Sign Size:	>=48-in		36-in		<=30-in		>=48-in		36-in		<=30-in	
Color:	W	R	W	R	W	R	W	R	W	R	W	R
All Signs:	35	8	45	8	50	8	25	5	30	5	35	5

All table values in cd/lx/m²
1 mi/h = 1.6 km/h
1 in = 2.54 cm

Note: Since both the legend and the background of these signs is retrorefletorized a minimum maintained contrast ratio of 4:1 has also been established. If the retroreflectivity value for either the white or red material falls below the value specified in the table or if the retrereflectivity of the white material divided by the retroreflectivity of the red material is less than four, the sign should be replaced.

Source: FHWA

Table 10. Minimum retroreflectivity guidelines for white-on-green guide signs.

Legend Color: White
Background Color: Green

Traffic Speed:	45 mi/h or greater		40 mi/h or less	
Color:	White	Green	White	Green
Ground-Mounted	35	7	25	5
All table values in cd/lx/m^2 1 mi/h = 1.6 km/h				

Source: FHWA

To ensure that agencies replace signs that no longer provide the retroreflectivity levels prescribed by these tables, or their replacement, a program for timely sign inspection and replacement will be needed; hence, the need for a sign management system.

SIGN MANAGEMENT SYSTEM

A management system can be defined as an integrated and coordinated set of policies, procedures, methods, and tools that assist decision makers in providing a product in a serviceable condition in the most cost-effective manner. In the highway field, management systems have been created for pavements, bridges, traffic safety, and traffic congestion. An obvious extension of these management systems is in the area of traffic control devices and signing in particular. In this context then a Sign Management System (SMS) can be defined as a coordinated program of policies and procedures which ensure that the highway agency provides a sign system that meets the needs of the user most cost-effectively within available budgets and constraints. When fully developed, a comprehensive Sign Management System can effectively manage various activities that take place during the life cycle of highway signs from purchasing of materials or fabricated signs through the sign's service life and eventual replacement and recycling. As illustrated in figure 4 the activities throughout the life cycle of signs can be coordinated through series of programs within a computer environment.

A comprehensive sign management system consists of the following elements for various stages of the life-cycle of signs:

- Sign materials (sheeting, substrate, bracing, etc.) should conform to specifications of the agency, and selection of the appropriate material should consider cost, service life, and motorists' needs. The ability to track the cost and service life of various materials through a SMS will ensure that the agency is using the most cost-effective material for the specific user requirement.

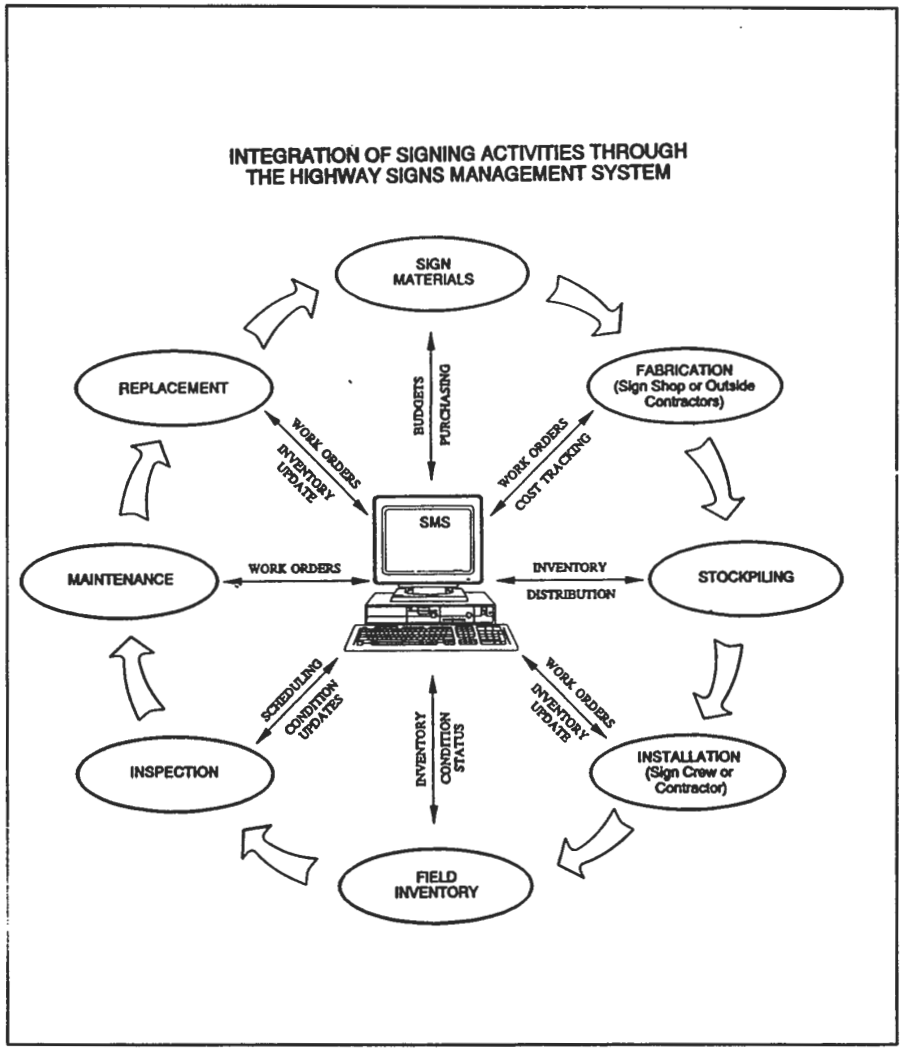


Figure 4. Integrated traffic sign management system.

- An effective SMS would provide the ability to forecast sign replacements, which would facilitate budgeting and scheduling of sign material or fabricated sign replacements.

- An inventory of stockpiled fabricated signs will allow managers to ensure timely replacement of signs.

- \n SMS can generate work orders for new sign installation by in-house sign crews or by contractors.

- The nucleus of an SMS would be the inventory of the signs on the road network. That inventory is maintained through the computer and a work order system that ensures updating whenever sign activities occur.

- Periodic inspections of signs is necessary to insure that they are maintained at a serviceable level and continue to meet the users' needs. An SMS can be effective in scheduling inspections, recording the results, and determining when signs may need to be replaced.

- Inspections will identify maintenance needs, such as sign cleaning, straightening of sign posts, removal of graffiti, clearing of view-obstructing foliage, etc. These maintenance activities can be scheduled through the SMS and the work accomplished including costs can be recorded with the SMS.

- The replacement of ineffective signs can be scheduled and the inventory can be updated through an SMS using work orders.

- Certain sign materials especially aluminum substrate and metal supports can be recycled and used for future sign requirements.

These sign activities, some of which will be discussed in detail in this guide, can be effectively coordinated using a computer and a series of interrelated software program modules.

SIGN INVENTORY[4]

Part and parcel of a sign management system is a sign inventory. One has to know what one has in order to manage it effectively. This general axiom applies especially to highway signing. While it is beneficial to know what the agencies inventory of signs and/or sign material is in the sign shop, it is highly desirable to know what is out on the road.

---

[4] This section, except for minor editing, was originally prepared by Jeff Paniati of FHWA.

is in the sign shop, it is highly desirable to know what is out on the road.

A comprehensive inventory can serve many purposes including:

- **Targeting Signs for Replacement** — tracking the installation dates of traffic signs allows the user to easily identify those signs that are most likely in need of replacement. When combined with an effective inspection program this allows the removal of signs that have reached the end of their useful life.

- **Identification of Problems** — maintaining records of maintenance activity allows the user to identify problem locations. Physical countermeasures can be utilized at high vandalism sites, while safety studies can be conducted at locations with frequent knockdowns. A well-maintained inventory is also important for identifying and quickly replacing missing signs.

- **Minimizing Tort Liability** — an inventory is an essential tool for use in tort liability cases. It can provide evidence of the existence of a particular sign at a particular location and document the inspection or maintenance activity associated with the sign. An inventory can also be an effective tool for identifying non-conforming signs as standards are changed. Some insurers have recognized the value of sign inventories in reducing liability. For example, the Utah Risk Management Association offers a 3 percent discount on insurance premiums to jurisdictions with a sign inventory.[5]

- **Planning and Budgeting for Sign Replacement** — knowledge of the numbers and ages of signs allows the manager to establish a regular program of sign replacement. This can include identification of signs to be replaced, estimation of material quantities, routing and scheduling of replacements, etc. The inventory allows the manager to make informed decisions and to allocate limited resources in a cost-effective manner.

- **Maximizing Productivity** — combining work orders with a sign inventory allows the manager to monitor the productivity of signing activities and to effectively schedule both emergency and regular maintenance activities.

If the inventory is to be successful in providing these functions and meeting the needs of the user, then it must be well designed. The following is a seven-step process for the planning and development of an effective sign inventory.

Step 1: Involving Key Personnel

The development and maintenance of an effective sign inventory is a significant undertaking. It can involve a substantial investment on the part of the jurisdiction. Reaping the benefits of this investment requires the commitment and participation of individual responsible for:

- Collecting Data
- Entering Data
- Installing Signs
- Maintaining Signs
- Inspecting Signs
- Using the Inventory

The success or failure of the inventory depends on the communication between the personnel involved more than any other aspect. The best planned system, using the latest in computer hardware and software will not be successful if those responsible for collecting and maintaining the data do not see the value of the sign inventory. It is essential that individuals responsible from each of the areas listed above actively participate in the planning, development and implementation of the inventory. In small jurisdictions this may involve only a few individuals, in larger jurisdictions it may require a steering committee with representatives from each area. Regardless of the size of the group, they should be consulted throughout the process and their input used to guide the development and refinement of the inventory.

Step 2: Selecting a Location Reference System

The establishment of the location reference system provides the foundation on which the inventory will be built. In many jurisdictions, one or more location reference systems may already exist. If a standard location reference system has been established for the jurisdiction, then clearly the sign inventory should utilize this same system. Use of a common location reference system brings about many efficiencies (utilization of measurement tools, training of personnel, linking of data bases, etc.) and is highly desirable. If multiple reference systems exist or in the absence of any established location reference system, the user group must select the system that will be most effective in meeting the needs for signing. Alternative location reference systems include:

- **Route/Milepost/Distance** — this system is primarily used by larger jurisdictions that have physical markers at regular intervals [usually 1-mi (1.61-km) spacing] along the roadway. Signs are located by the distance from the nearest milepost. Distances are recorded as positive if they are in the direction of increasing mileposts and negative if in the direction of decreasing mileposts. A variation on this approach is the reference post system. With this approach sequentially numbered reference posts

are placed at irregular intervals along the roadway. Signs are located by the distance plus or minus from the nearest reference post. The advantage of the reference post approach occurs when alignment changes are made to the roadway. With the milepost system all of the markers and data along the route within and after the change must be reassigned. With the reference post system only data within the changed section is affected.

- **Route/Milepoint** — with this system signs are located at a milepoint (normally specified to the hundreds or thousandths of a mile) along a route. This system may be used with or without markers on major physical features such as bridges. Where physical markers do not exist, roadway features such as intersections, bridges, etc. are given a milepoint (and milepoint maps, straight-line diagrams, or listings of roadway features and their milepoints are used for reference). This system is the most common for rural locations. Use of vehicle-mounted electronic distance measurement devices can significantly increase the quality and efficiency of measuring distances in the field.

- **Link/Node/Distance** — with this system, intersections (and often other physical features) are given node numbers and the roadway sections between the nodes are designated as links. Links are numbered using the node numbers at either end of the link. For example, the link between nodes 1 and 2 would be known as link 1-2 if you were traveling from node 1 to node 2, and link 2-1 if your were traveling from node 2 to node 1. Signs are located by a distance (either in miles or feet) from the beginning of the link. Reference point and control section systems are variations of the link/node approach. With these systems, roadway sections are numbered (similar to links) and signs are located by a distance from the beginning of the control section or from the last reference point. As with the milepoint system, maps or listings are used in the field for reference. The advantage of the link/node system (and the reference point and control section systems) is similar to that for the reference post method. If construction is done lengthening or shortening a route, only the affected links have to be changed, not the entire route. One disadvantage of this system is that the link and node numbers by themselves are meaningless to the field user and must be tied back to a route name.

- **Route/Intersection/Direction/Distance** — with this system, signs are tied to specific intersections and are located by their distance away from the intersection in a particular cardinal direction. This system is typically used in urban areas with closely spaced intersections. In rural areas with long distances between intersections this system is very inefficient due to the need to find an intersection to use as a reference. To be effective, this system requires that consistent cardinal directions be established for each intersection. Without this consistency, one user may identify a particular leg of the intersection as west, while another would call it northwest or southwest. A variation of this system is to locate signs by their distance from one intersection

toward another intersection (sometimes referred to as the "from/to" or " A street/B street" method). For example, a sign might be located on Main Street, 50 ft (15.2 km) from the intersection with Elm Street toward the intersection of Maple Street. A disadvantage of either approach is the need for a map to identify adjacent intersections.

- **Latitude/Longitude** — with the advent of Geographic Information Systems (GIS) for the integration and display of data and the Global Positioning System (GPS) for the location of data, latitude/longitude coordinates have become another option for establishing sign locations. With a hand-held GPS receiver (or a GPS card in a portable computer) the user can obtain latitude and longitude coordinates for a location on the ground. While GPS is not affected by cloud cover or electrical interference, it can be blocked by tall buildings in urban areas or tree cover in rural areas. Effective use of GPS data also requires the availability of GIS base-maps on which to display the data and relate the data to other reference systems that can be used to locate signs in the field. GPS and GIS applications are still in their infancy in the highway community, but if well-developed they clearly offer the potential to significantly increase the accuracy and efficiency of locating and displaying sign data.

More detail on location reference systems can be found in a National Cooperative Highway Research Program synthesis study on highway location reference systems.[6]

In addition to the longitudinal location reference systems described above, the user must decide whether to reference individual signs or sign supports. Some inventories treat each sign as a unique record while others use the sign support as the basic record and then reference signs to the support (a one support to many signs relationship). Both systems have their advantages and disadvantages.

The referencing of individual signs is the most commonly used approach. This is especially true in smaller jurisdictions with relatively few supports with multiple signs mountings. The selection of the sign support as a referencing method may be advantageous for jurisdictions with a large number of supports with multiple signs. It eliminates some of the data redundancy by requiring the user to only enter the support information one time and then referencing a number of signs to that support. It does require the development of a system for identifying the sign location on the support (often a sequential numbering system starting from the top left and proceeding clockwise is used).

The selection of the longitudinal and sign reference systems should be made in conjunction with the selection of the inventory software (see Step 4), since many off-the-shelf software programs will support only one (or a limited number) of these reference systems.

Step 3: Choosing Data Elements

Having selected a location reference system, the next step in the process is to determine what data elements will be collected. There are a wide range of data elements that can be collected and used in the management of signs. Each individual user must weight the usefulness of the data versus the costs required to maintain the data. The major expenses of data collection are often associated with the travel time required to get to the signs in the field and the costs required to make field measurements. Once in the field the incremental cost of collecting additional data elements is relatively small. For most data elements, the decision whether or not to collect the data will be based on the usefulness of the data for managing the inventory and the ability of the agency to maintain the data.

The following listings provide the data elements that should be considered when developing an inventory. The data elements have been categorized into three groups based on the importance of the elements: core, critical, and desirable. They are described below.

Core Elements — these data elements are essential for effective sign management and should be included in every inventory. An inventory containing these elements will provide information on the location of signs, their condition, and any maintenance activity that has been conducted. This will allow for a basic inventory that can identify signs needing replacement, be used for tort liability defense and provide some limited management and budgeting capability. Table 11 provides a listing of the core data elements.

Critical Elements — these data elements significantly increase the value of the sign inventory and should be given serious consideration. The addition of details of the installation date and the characteristics of the sign and supports provide a much greater ability to target signs for replacement and develop cost-effective sign replacement plans and budgets. Table 12 provides a listing of the critical data elements.

Desirable Elements — these data elements may add value to the inventory depending on the needs of the individual user. They provide more detail on the sign installation. Table 13 provides a listing of the desirable data elements.

The user group identified in Step 1 should be used as a resource in selecting the desired data elements. The selection process should not be comprised by the data elements that users "want," but rather the data elements they "need." Surveying users wants can result in unrealistic "wish lists" of data elements. It is important that the final selection only include those elements that will serve a well-defined need and for which there is a commitment to maintain.

Table 11. Core data elements.

DATA ELEMENT	DESCRIPTION
Location	Includes several variables (such as route name, distance, etc.) depending on the location reference system that is selected.
Position	Location of the sign relative to the road (e.g. left, right, overhead, median).
Sign Code	Usually based on the MUTCD designations, may be supplemented or modified based on State or local sign designations.
Sign Condition	An assessment of the quality of the sign based on daytime and nighttime visual inspections.
Maintenance Activity	Maintenance activity associated with a particular sign.
Inspection/Maintenance Date	Date when the sign was inspected or maintained.

Table 12. Critical data elements.

DATA ELEMENT	DESCRIPTION
Installation Date	Date when the sign face was installed.
Sign Size	The width and height of the sign.
Sheeting Type	Grade of retroreflective sheeting.
Backing Type	Type of sign blank material.
Post/Support Type	Type of sign support used, may include breakaway characteristics.
Post/Support Condition	An assessment of the quality of the sign support.
Sign Orientation	Cardinal direction the sign is facing.
Traffic Speed	Speed limit on the roadway where the sign is located.

Table 13. Desirable data elements.

DATA ELEMENT	DESCRIPTION
Offset	Distance from the edge of pavement.
Height	Height of sign above the level of the road at the edge of the pavement.
Retroreflectivity	Objective measure of the nighttime quality of the sign.
Inspector	Name or initials of the individual who inspected or maintained the sign.
Sign Identification Number	A unique number identifying the sign.
Images	Visual images of the sign, either digitally captured or linked to a videodisc-based photolog.
Comments	Supplementary notes about the sign installation.
Other Reference Numbers	Could include maintenance district, plan or contract numbers, etc.

Step 4: Selecting Inventory Software

In the past, small jurisdictions used paper-based methods for maintaining sign inventories, while large jurisdictions that could afford computer systems had to resort to mainframe-based applications. Neither was very effective in meeting user needs. Paper-based systems were difficult to maintain and severely limited access to the data. While some excellent mainframe computer-based systems were developed, the majority were expensive to maintain, not user-friendly, and required sophisticated programming to make any changes to the system. The introduction of the microcomputer opened up a whole new range of options for developing inventories. The cost of hardware dropped dramatically and a range of software approaches including spreadsheet and data base software packages could be used to develop inventory systems.

Today, even the smallest of jurisdictions have access to microcomputer hardware and a wide range of public and private domain off-the-shelf software packages have become available to the user. The options include:

- **Customized Programs** — If a primary objective is to have a system that exactly matches the user's needs, then a customized sign inventory software application may be appropriate. As more and more jurisdictions move toward Geographic Information Systems, the sign inventory may be just one of a series of data management applications that are developed. If experienced software development capabilities are not available in-house they can be contracted for. While this approach allows the software to be tailored to fit the jurisdiction's needs, it often comes at a significant cost. These costs include initial development of the software and ongoing maintenance and support. For most smaller jurisdictions, the costs of this approach are prohibitive. For State highway departments, customized programs likely will be required due to the need to integrate the sign management system with other information systems and to the large number of potential users at both control and district levels.

- **Off-the-Shelf Software** — For users with limited budgets or those who are willing to be more flexible, a number of off-the-shelf packages have been developed in recent years. These include both public domain software available from local technology transfer centers, and the MCTRANS and PCTRANS transportation software clearinghouses at very nominal costs. These public domain packages range from rudimentary to very sophisticated. Similarly, there is a wide range of proprietary software packages available. These packages can be found in both MCTRANS and PCTRANS and through advertisements in magazines such as the *ITE Journal*. Costs for these software packages range from several hundred dollars into the thousands of dollars. For additional fees, some of the vendors will make minor changes to customize the software to better match the needs of an individual jurisdiction. While most of the software packages available were developed strictly for sign inventories, several larger packages that include additional modules for the management of markings, lighting, traffic signals, etc. are available as well.

  While there are many more off-the-shelf products available that could be discussed here, some offer unique capabilities. One of these is the FHWA Sign Management System which includes sign deterioration models that predict when a sign is likely to need replacement. These models allow the user to estimate future budget requirements for sign replacement. Appendix A provides a summary description of the SMS program, which is fully explained in the User's Guide.[7] Figure 5 shows the data elements, the predicted R_A value and the estimated replacement data for a typical sign.

At least one commercial program offers the capability to record and store digitized color images of the sign as illustrated in figure 6. While the hardware necessary to collect the data and store the images is significantly more expensive than most inventory systems, the availability of the image can be advantageous especially for unique message signs such as guide signs.

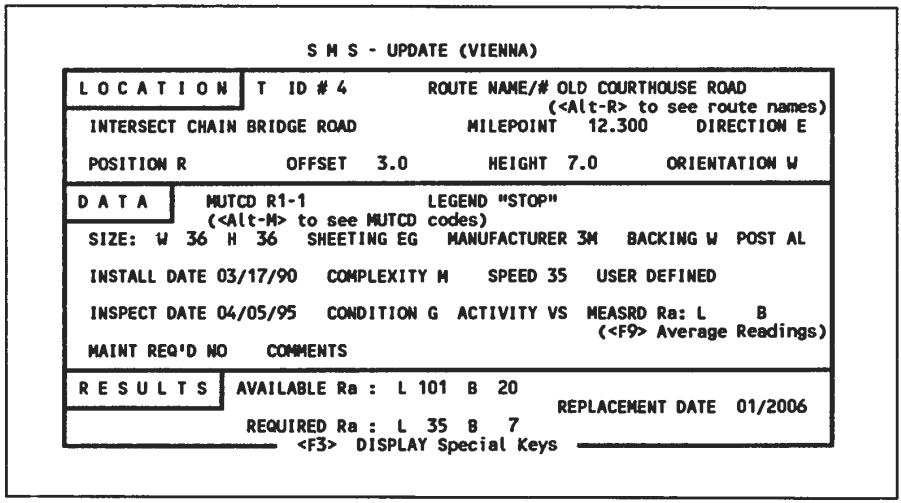


Figure 5. FHWA sign management system.

- **Turn-Key Systems** — A third option that is available, are turn-key systems, There are a number of consultants who have developed sign inventory software packages, that market the software along with their data collection services. These firms are skilled in data collection and for a fee (either a flat fee or a per sign cost) will collect the data and provide the user with a complete operational inventory that includes both the software and the inventory data. Firms offering such services can be found through advertisements in magazines such as the *ITE Journal*. This type of approach can be useful for jurisdictions with limited manpower to collect the initial inventory data.

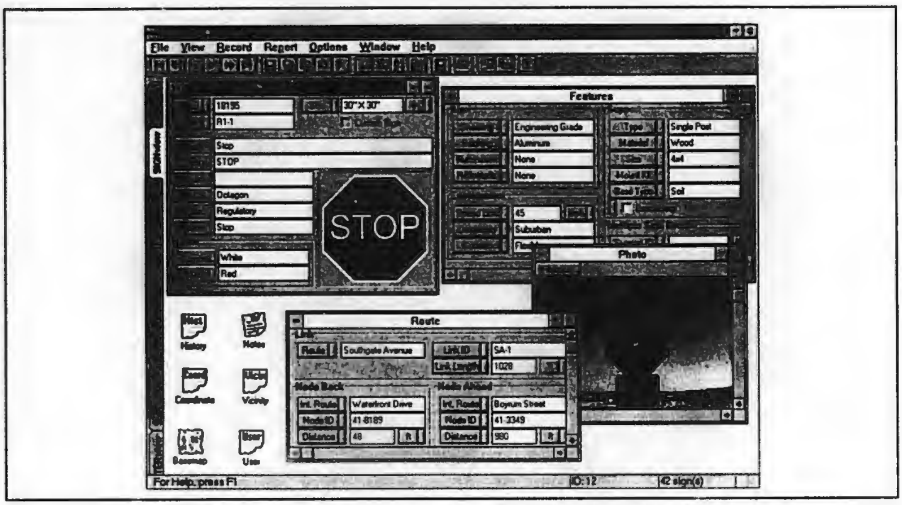


Figure 6. Example of an inventory program that includes sign picture.

Step 5: Preparing for Data Collection

Having selected a location reference system, defined the data elements to be collected, and selected a software package, the inventory administrator must now make the final preparations for the actual data collection. This preparation is a two-part process. The first part involves establishing definitions, conventions, etc. Some of the issues that should be addressed prior to beginning full-scale data collection are:

- **Route Names/Numbers** — The inventory administrator must select a standard approach to naming routes. Will route names or numbers be used? For routes with multiple names, which name will be selected. It is important to define the route names initially to avoid multiple names for the same route. Software that includes look-up tables for route names can assist in this process. If this capability does not exist in the software, then a standard route name list should be developed.

- **Ramps/Service Roads** — Larger jurisdictions with grade-separated interchanges will have signs on ramps, unnamed service roads, or rest areas. A naming convention must be developed for these sections of road so that the signs can be properly located. One approach that can be used is to assign them names or numbers based on their location relative to the mainline of the roadway. For example, ramps may be designated by the milepost of the interchange and sequentially numbered.

- **What signs to include?** — Will the inventory include just regulatory and warning signs or will it also include street name signs, parking signs, post-mounted delineators, etc.?

- **Whose sign is it?** — Often the development of a sign inventory forces jurisdictions to determine who is responsible for signs at jurisdictional boundaries. The most frequent point of confusion are signs at intersections of routes maintained by two different jurisdictions. The inventory administrator should determine if an agency policy exists. If not, one should be defined.

For most of these issues there is no right or wrong answer. The important thing is that a consistent policy be established, recorded, and communicated to all users.

The second part of the preparation process is training of the data collectors, which is key to the success of the collection effort. This training should include not only the individuals who will be building the inventory, but also those who will be responsible for maintaining the data. The policies established in the first part of the preparation will from the core of this training. In addition, the inventory administrator may need to develop data collection forms and instructions, inspection guides, etc.

Step 6: Initial Data Collection

The initial data collection effort to establish a sign inventory requires a significant effort. Many jurisdictions will not be in a position to hire an outside consultant or devote a large amount of staff to collect the data in a short period of time. Normally, the initial data collection will be conducted over a period of months or even several years. As a result, it is critical that the data collection be organized in a way to allow a subset of the inventory to become operational as quickly as possible. The type of subset selected depends on the jurisdiction, but could involve breaking up the inventory by roadway class (Interstates, U.S. routes, State routes, local routes, etc.), by townships, by maintenance districts, or by sign types (regulatory, warning, street name, parking). Another option is to quickly collect a few core and critical data elements (location, sign type, condition, etc.) and gradually collect other data elements as time allows. The key is to pick a cohesive group that will result in a useful inventory.

The benefit of this approach is that it will quickly produce a working inventory that can be used and maintained. This allows the agency to begin accruing the benefits from the inventory and demonstrating its usefulness. This can be important in obtaining continued support for the full development. Starting with a small piece of the entire system also allows the inventory collection and management procedures to be tested and refined.

Three basic methods are available for collecting sign inventory data:

1) **Manual Field Data Collection** — Manual field data collection is the most widely used method to gather the initial data for a sign inventory. Using this approach one or more persons equipped with data entry forms and measurement tools collect the data. Depending on the location reference system and the size of the jurisdiction, various methods can be used to establish the location of the sign. These methods range from the use of a measuring wheel to a vehicle-mounted distance measuring device to a hand-held GPS receiver. Establishing the location of the sign is often the most difficult and time consuming part of the data collection. One recent study, found that use of GPS receivers for obtaining location reference information for urban signs was approximately 20 percent faster than data collected manually using traditional measurement techniques.[9]

   Once the location is established, a combination of visual observations and measurements are used to gather the inventory information. The amount of time required for this task will be dependent on the data elements selected for inclusion in the inventory. The manual approach is labor intensive, but relatively simple. With minimal training and a well designed data collection form, the data can be quickly gathered in the field and entered into the computer system back at the office.

2) **Microcomputer-Based Field Data Collection** — With the decrease in the cost, size, and weight of portable microcomputers, direct entry of field data is now a viable option. Many jurisdictions and sign inventory consultants now use this approach. The location of the sign may be established as with the manual approach described above or may be recorded directly into the computer. Distance-measuring devices and GPS receivers that can be integrated into the computer allow the data to be stored directly into the sign record eliminating data entry errors and reducing data entry time. Other sign inventory data can be keyed directly into the computer, eliminating the need for data reduction back at the office.

   Another recent advance in the microcomputer area has been the development of pen-based computers. These computers allow the user to enter data by touching the screen with a pen. This can speed the data entry process by minimizing or eliminating keyboard entry. This technology is being widely investigated for a variety of transportation-related applications including maintenance management, accident data collection, etc. This approach was successfully used in the development of a sign inventory for the New Jersey Department of Transportation. This inventory covers 16,000 mi (25,744 km) of roadway and includes over 150,000 signs.[10]

   More details on emerging technologies for data acquisition can be found in recent reports by the Federal Highway Administration and the Transportation Research Board.[11,12]

3) **Photologs/Videolog-Assisted Data Collection** — If available, photologs or videologs can be used as a starting point for the sign inventory. Photologs consist of sequential images of the highway taken from an instrumented vehicle. Traditionally, photologs are taken using a 35-mm motion picture camera modified to take individual frames of film at preset distances (normally one picture every 59 ft [18 m] or every 26.2 ft [8 m]). Videologging is similar to photologging, however, continuous images of the roadway are taken instead of individual pictures at preset distances. In recent years jurisdictions have begun to use videodisc-based photolog systems instead of the traditional film-based systems. In this system, the film images are transferred to videodisc or a shuttered video camera is used to record directly to the videodisc. Videodisc-based systems offer the advantage of reduced storage costs and increased accessibility.

   Using this technique basic information such as the location of the sign, sign type, support type, etc. can be gathered through visual observation of the photolog images in the office. The collection of measurements such as the offset, height and size of the sign can be estimated by overlaying a grid on the screen. Precise measurement of these elements and determination of the elements such as the sheeting type or backing type must be made in the field, however.

   An important issue that must be addressed when using this approach is the ability to read the legend on the photolog image. The Connecticut DOT (ConnDOT) recently completed a pilot study to develop a videodisc-based inventory system.[13] One of the problems they encountered was the ability to read the sign legend on the photolog image. In this effort they found that 45 to 70 percent of the signs, depending on sign location, were not legible using normal inventory images taken every 59 ft (18 m). However, using a second, close-up image of the right side of the roadway, they were able to increase the legibility to approximately 90 percent.

The data collection costs for the inventory will vary depending on the data collection approach used and the number and type of data elements collected. ConnDOT estimates that the costs of developing a base inventory for the estimated 170,000 signs on the 8,000 mi (12,872 km) of State system using a manual field data collection method would be approximately $163 per mile ($100 per km) or $7.65 per sign. Using the videodisc-based inventory, supplemented with field data collection, ConnDOT estimates their collection costs at $58 per mile ($35.90 per km) or $2.72 per sign. Based on the estimated costs for alternative road inventory procedures from earlier work by Datta and Herf and cost information provided by various jurisdictions, it is estimated that the cost of manual data collection ranges from $4 to $9 per sign, microcomputer-based data collection from $3 to $7 per sign, and photolog-assisted data collection from $2 to $5 per sign depending on the data elements collected, size of the inventory, etc.[14,13,15,16]

Step 7: Maintaining the Inventory

As is evident from the previous discussion of costs, the development of a sign inventory is a significant investment. This investment can easily be wasted if the groundwork for maintaining the inventory has not been laid early on in the development of the inventory. The inventory administrator must identify all installation and maintenance activities (including those done under contract by private forces) that affect the data elements selected in Step 4 and develop a process for ensuring that these activities are reflected in the inventory.

Since most jurisdictions already have some work order system in place for assigning work and accounting for labor and materials, integration of the collection of the necessary sign inventory data with the work order is usually the most effective approach. Depending on the data elements selected and the information already being collected as part of the work order, only minor modifications to the form itself may be necessary. The National Cooperative Highway Research Program Synthesis "Maintenance Management of Street and Highway Signs" contains several examples of work order forms.[17]

As critical as the design of the form, is the timely processing of the data collected. In developing the process for maintaining the inventory, a defined sequence should be identified for routing copies of the completed work orders to the individual responsible for data entry. While in small jurisdictions, this person may have numerous other responsibilities, time must be set aside to allow regular data entry. If changes to the system are not entered in a timely manner, the inventory can become out of date and unreliable as a daily working tool. Users will quickly lose faith in the system if this is allowed to happen.

As with the initial data collection, microcomputer-based data collection can be used to directly record the data in the field. The field data can then be uploaded to the complete inventory, in the office, at the end of the day. This eliminates the need for data entry and puts the inventory, out in the field, in the hands of the end-user. If this approach is used, it is important that the software include good edit checking to spot data entry errors and regular quality control checks by the inventory administrator to ensure accurate data is being entered.

SIGN INSPECTION

The routine inspection of traffic signs to ensure their effectiveness is a critical component of a comprehensive sign management system. Periodic inspection of signs should be a standard operating procedure of the agency responsible for motorist safety. Signs can be deficient in any number of ways; hence, items that should be checked include:

- Condition of sign face — indications of major cracking, delamination or peeling or blistering of the retroreflective sheeting materials, missing message, etc.
- Discoloration, streaking, or fading of the sign face.
- Visibility of the sign — roadside vegetation or a new structure may be blocking the motorists' view of the sign.
- Dirt or other substance on the sign.
- Vandalism.
- Orientation and structural stability of the sign support system.
- Usefulness or appropriateness — some signs may no longer be needed and should be removed.
- Poor retroreflectivity level.

To detect and then resolve any and all of these deficiencies, a comprehensive sign inspection program is required. This would include formal scheduled inspections by trained sign crews and even staff engineers as well as informal observations by personnel of various agencies including the highway and police department and even postal carriers or other public agencies that travel the routes frequently. The department responsible for signing should solicit the assistance of all appropriate departments and establish a procedure for receiving notices of a potential signing problem.

Most of the problems listed above can be identified by a visual inspection during the day by trained personnel. If the personnel are adequately trained and sensitive to observing these deficiencies, problems can be identified on a daily basis as they travel along the routes. However, it will still be necessary to conduct a formal inspection at least annually. Programs and procedures for conducting sign inspections can be found in "Maintenance Management of Street and Highway Signs" and in the Institute of Transportation Engineers' publication *Traffic Sign Handbook*.[17,18] This guide will focus on the methods for inspecting for retroreflectivity condition.

One of the deficiencies which can not be detected by a daytime visual inspection is the sign's level of retroreflectivity. Over time all signs will experience diminishing retroreflectivity levels. This deterioration will result from the ultraviolet portion of sunlight, moisture, high daytime/low nighttime temperature cycling, pollutants, and even chemical reactions between the sheeting and the substrate (i.e. aluminum panel). Also, loss of retroreflectivity can occur from vandalism (i.e. gun shots, spray paints, etc.).

Inspection for loss of retroreflectivity can range in sophistication and involve either subjective visual inspections or instrument inspections. The selection among the alternatives is dependent upon the resources (funds, personnel and equipment) of the agency. The location (overhead vs. ground mounted), number of signs, and other logistical factors may also influence the inspection method.

Visual Inspection Methods

There are a number of alternative visual inspection procedures that can be employed to determine if a sign has lost its effective luminance and may be near or below the minimum maintained R_A values. The most simple is to drive along at night and observe for obviously deficient retroreflective signs. This procedure can be very efficient if the inspector is experienced enough to know when a sign is ineffective and specifically when it is at or below the minimum R_A values. Research conducted for the State of Washington has demonstrated that inspectors can be trained to visually detect signs within certain levels of retroreflectivity.[19]

The key to relying purely on a subjective visual assessment is to select the most appropriate inspectors and train them to relate a visual assessment of luminance to an actual R_A value. If possible, the inspector(s) should be older than 50 because research has shown that older drivers have impaired nighttime vision and require brighter signs. Training of new inspectors would involve having them view signs of different colors at various levels of retroreflectivity. To do this, the agency should keep a supply of signs at the maintenance yard for this purpose. Even after suitable training, it is a good idea that each inspector view the test signs, especially those at or near the minimum values, just before the night inspection run.

As an aid to this visual inspection, a sign inspection pamphlet has been published by FHWA.[22] The pamphlet includes night photographs of signs at different levels of retroreflectivity. While photographic images are not totally reliable and do not replicate exactly what a person sees, they can provide the inspector another aid in judging the retroreflectivity adequacy.

Another aid to the visual inspection procedure is to use a test panel — a small (no greater than 12 in [0.3 m] square) panel of sheeting that has a retroreflectivity level equal to (or nearly so) the minimum value for that color. The test panel can be attached to the "questionable" sign using either masking tape or a clamp. Stepping back about 30 ft (9.1 m), the observer should hold a flashlight about 2 in (50.8 mm) from his/her eyes and shine it at the sign. If the inspection guide is brighter than the sign, the sign should be replaced.

Nighttime inspection is often not feasible for administrative reasons; for example, the inability to pay overtime if that would be necessary. If this is the case a daytime visual inspection procedure using a hand-held high-intensity light beam may be used. When a high-intensity q-beam of about 200,000 candlepower is flickered across the face of a sign during the

day, it will show a "glow" of returned light if the retroreflectivity level is still adequate. The effectiveness of this procedure is affected by the ambient light conditions and, therefore, is not very precise. However, with some training an inspector can detect obviously inferior and failing signs with this method. The Mississippi Department of Transportation has used this inspection method for a number of years; their traffic engineering department can provide guidance on how to perform this procedure.

Inspection by R_A Measurement

The best method to determine if a sign has reached its minimum R_A level is to measure the signs retroreflectivity in the field. This can be accomplished by using a commercially available retroreflectometer, such as manufactured by Advanced RetroTechnology, Inc. Figure 7 shows an inspection being performed using their Model 920 Field Retroreflectometer and figure 8 shows the apparatus in more detail. (As this document was being completed Flint Trading, Inc. announced the availability of another hand-held retroreflectometer know as the Retro Sign®. Information was not available on this product.) This device can be used during the daytime. However, as is evident from figure 7, it requires that the inspector be at the sign to make the measurement.

The retroreflectometer will come with instructions on how to use the instrument. In addition to those instructions, the following is recommended:

1) Make sure the instrument is properly calibrated as found in the instructions; a faulty reading will occur if this is not done.

2) Take a reading from at least four areas of each color, which can then be averaged for recording purposes. Black areas do not require measurements because they are not intended to be retroreflective.

3) An extension pole can be purchased which will allow access to nearly all roadside mounted signs. A bucket truck will be required for overhead signs.

4) Follow standard traffic control procedures for maintenance activities prescribed by your agency and as found in Part VI of the MUTCD.



Figure 7. Sign inspection using model 920 retroreflectometer.



Figure 8. Components of the model 920 retroreflectometer.

Measurements using a retroreflectometer will take considerable time and therefore, it is not necessary that every sign be measured each inspection period. Measurements could be limited to those signs that were identified during a nighttime visual inspection or the daytime inspection with the q-beam. Also, if the inventory system has the capability similar to that of the FHWA's SMS program, it could be limited to signs that have been identified as requiring inspection by the program.

It would be highly desirable to be able to measure the retroreflectivity level of a sign during the day from a moving vehicle. Such a device has already been developed. Initially developed under a contract with the National Cooperative Highway Research Program, a second generation has been developed by the FHWA. Figures 9 and 10 are inside- and outside-vehicle photographs of the system which has been named the Sign Management and Retroreflectivity Tracking System (SMARTS). While the vehicle is moving the operator aims the tracking/video system at the desired sign. The system will automatically track the sign and at 200 ft (61 m) will flash the sign with a powerful flash tube. The recording system captures the retroreflectivity levels of all colors within the image and a picture of the sign (image). This information along with the GPS coordinates the other data associated with the sign and are stored in the systems data base. This data can be used to evaluate the quality of the sign and can be used for establishing and modifying the sign inventory data base. When fully developed a mobile system will allow periodic inspection of retroreflectivity levels of all traffic signs to be performed fairly efficiently. However, since the apparatus is likely to be expensive, approximately $100,000, it is likely that only a few local agencies, outside the State highway department, could afford to have their own. It is much more likely that either private enterprise will purchase these and provide the inspection service on a per distance or per sign basis or that the State highway department will "loan" the apparatus to the various local agencies.

SIGN MAINTENANCE

In the context of a sign management system, sign maintenance involves all activities, short of replacing a worn-out sign, that keep the sign effective. Typically these activities could involve:

1) Cleaning of the sign face due to normal dirt accumulation.

2) Removal of spray paint and other markings from vandalism.

3) Maintaining adequate visibility to the sign by cutting back or removing foliage.

4) Reorientation of the sign.

5) Replacement of the sign post damaged by a knock down.

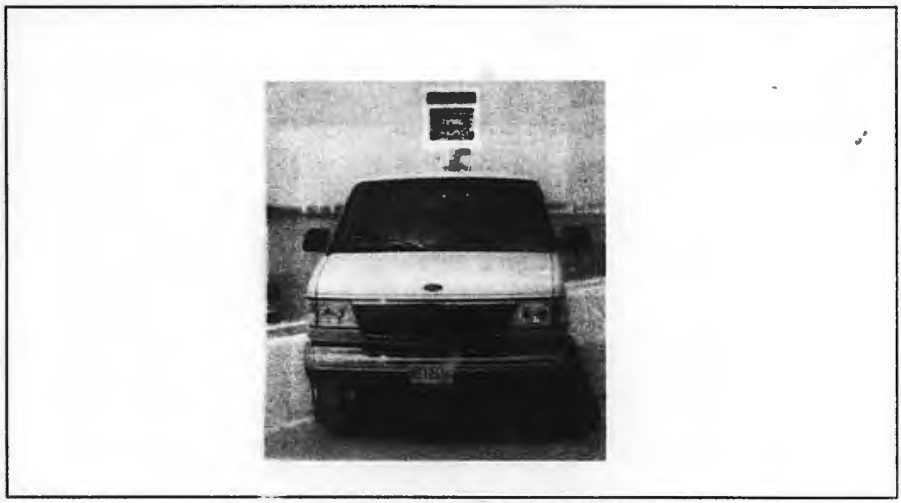


Figure 9. Exterior view of FHWA's SMARTS.

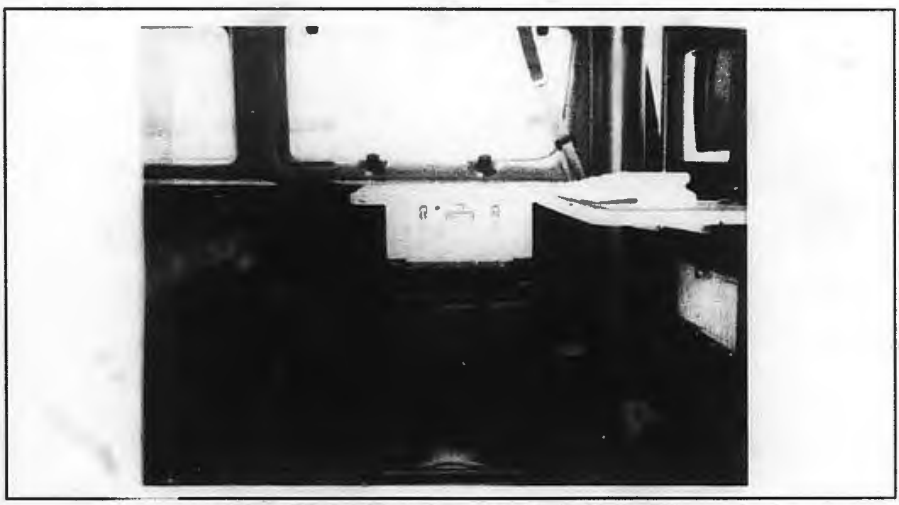


Figure 10. Interior view of FHWA's SMARTS.

With regard to sign cleaning, most agencies, State and local, do not, as a standard practice, clean their signs on a regular schedule, annual or otherwise. In most cases, the "washing" of the sign by normal rain will remove most accumulation of residue from various sources. At least one State agency that evaluated this practice determined that while some signs benefitted from washing, in general it was not worthwhile to do so.[17] However, there are many instances and situations where periodic washing is necessary to ensure that the normal life of the sign is attained. Signs that are vulnerable to excessive residue build-up that may not be washed away by rain include:

- Signs on heavily traveled truck routes especially at locations where trucks must stop. Over time the diesel fumes will significantly discolor the sign and render it ineffective.

- Signs directly under certain trees which exude resins. Signs placed under the canopy of trees such as oaks and pines are often discolored from this phenomenon. The discoloration is not easily removed by normal rainfall.

- Geographic areas with little annual rainfall.

- Signs within tunnels and under structures.

The effect that washing will have on an individual sign will likely vary by its age, type of material, and the environmental conditions. For a study on the retroreflectivity service life of signs conducted for the FHWA in 1991, the researchers found that washing signs increased the R_A value by an average of nearly 12 percent for engineering grade (Type I) sheeting (sample size of 336 signs of varying years of exposure and varying geographical locations) and nearly 8 percent for high intensity grade (Type III and IV) sheetings (sample size of 251 signs).[18] The newer encapsulated sheeting materials are apparently less affected by dirt accumulation.

Before replacing a sign, the agency may want to consider washing the sign. However, this extra maintenance activity may not be worth the additional effort, unless it is obvious that the sign has a significant dirt accumulation which is masking its retroreflectivity condition.

The washing of signs can be accomplished by using either a high pressure sprayer mounted on the back of a truck or by a standard cloth or squeegee attached to a long pole. Just water or a mild detergent is usually sufficient to remove most dirt buildup. However, it is best to consult with the supplier or manufacturer of the material, especially if a warranty is being provided.

The retroreflectivity of signs that have been vandalized by spray painting will certainly be adversely affected. Some manufacturers claim to provide retroreflective sheeting materials for which spray painting can easily be removed with normal washing.

Maintaining unobstructed line of sight to the sign is extremely important. Vegetation of all types can quickly block the motorists' view of the sign, making it ineffective both day and night. In areas where this is a problem, agencies should have a routine maintenance program whereby vegetation is cut back or removed as appropriate.

It is a good idea that a record of any and all of these maintenance activities be kept. Many of the computer inventory programs have the capability of recording the date and type of maintenance activity performed for each sign and keeping an historical record.

Additional information and procedural guidance for all aspects of sign maintenance can be found in Maintenance Management of Street and Highway Signs.[16]

SIGN REPLACEMENT OPTIONS FOR MEETING MINIMUM RETROREFLECTIVITY LEVELS

As noted earlier in this guide, minimum R_A values have been established for four groups of signs. These guidelines should be considered as values that marginally meet the retroreflectivity needs of most drivers. In many situations, and for some drivers especially those who have diminished night acuity, significantly brighter signs are needed. However; nor does it mean that if the R_A is just slightly lower than the minimum that it is totally ineffective. However, the minimum values do indicate the sign should be replaced soon.

All agencies have a limited maintenance budget, and therefore, must have a cost-efficient sign replacement program. To replace signs much sooner than when they reach their minimum R_A value will have the benefit of providing brighter signs to motorist, but it will likely increase the agency's cost for signing. On the other hand, replacing signs after they have reached their minimum R_A value may have several repercussions, including:

- Increased nighttime accidents due to deficient retroreflectivity levels.
- Increased motorist delay due to motorists not seeing or being able to read guide signs and thereby missing a turn.
- Increase motorist irritation due to their inability to read signs at night.
- Increased potential for tort claims because the sign's low R_A is considered a factor in an accident.

The last issue will have a direct negative financial impact on the agency. One large monetary judgement against the agency can far outweigh the agency's budget for sign maintenance.

It would seem, then, that the goal for an agency is to have a sign replacement program that *cost-effectively* identifies and replaces those signs that are approaching or at the minimum R_A requirements. This can be accomplished through a sign management system with varying levels of sophistication commensurate with the agency's sign budget.

Table 14 shows four options that an agency can follow to ensure that its signs will meet the minimum R_A requirements. The table also shows, in the middle column, the key components of a sign management system that will be required, and in the third column appropriate comments are provided. It is emphasized that these replacement options consider only the retroreflectivity condition of the sign. However, signs will need to be replaced due to the other observed deficiencies mentioned earlier. These replacement options are discussed below.

Table 14. Sign replacement options[1]

OPTION	SMS REQUIREMENTS	COMMENT
1. Visual Assessment Only	* Nighttime Inspection * Minimum R_A Reference Sign or Panel * With or Without Inventory * No Special Equipment	- Marginally Acceptable - May Err - May Not Be Cost-Effective
2. Maximum Sign Life	* Sign Dating * Inventory w/Date of Installation * Relationship of Sign Life to R_A Value * No Special Equipment	- Acceptable - Eliminates Night Inspections - May Err - May Not Be Cost-Effective
3. Maximum Sign Life with Visual Assessment Verification	* Same as # 2 * Additional Nighttime Inspection	- Acceptable - Will Increase Cost Inspection - May be More Cost-Effective than # 2
3. Measured R_A Compared to Required R_A	* Inventory * Sign Dating * Reflectometer	- Desirable - Higher Inspection Cost - Highest Assurance that Signs Replaced when Required - Maximum Life of Sign

[1]Based on Retroreflectivity condition only.

1. Replace Based on Visual Assessment

The simplest, but less precise, method for replacing signs due to their low retroreflectivity level is to identify such signs through a visual nighttime inspection. The procedures for conducting such an inspection were discussed previously. This method is described as less precise, because without the use of a retroreflectivity measuring device, or at least a minimum R_A reference panel, the decision to replace will be based on a subjective opinion of the inspector. To avoid the error of rating a sign satisfactory, when in fact its actual R_A is at or below the required minimum, the inspector will need to be conservative in his/her subjective rating. Without any verification by a retroreflectometer, this will result in signs being replaced before they have reached their full effective life. However, if the inspector is sufficiently trained and experienced, then the agency may feel comfortable with this method, recognizing that some signs may be replaced too soon if the inspector is conservative in his/her appraisal or some signs may remain that should be replaced based on their actual R_A value.

Although an inventory can facilitate this simple approach, an agency does not necessarily have to have an inventory. The inspection, which should be accomplished at least annually, can be scheduled by a number of criteria, for example by:

- Sign types, e.g. all STOP signs one period, all warning signs another period, etc.
- Road types, e.g. all freeways one period, all residential streets another period, etc.
- Districts, e.g. all signs on all roads in a maintenance district or area for one inspection period, etc.

The decision on scheduling and routing for the sign inspection is best determined by the agency.

2. Replace Based on Maximum Sign Life

Another option is to replace signs simply by their age. As of now there is no definitive data on the service life of various types of sign materials. The various manufacturers claim their material will last a certain number of years and some will provide a warranty for that period. However, there has yet to be a definitive study that indicates that certain materials will reach the minimum R_A value in a certain number of years. (One of the advantages of the FHWA SMS program that was discussed in this Guide is that it includes a program for monitoring the service life of different materials and establishing the expected life of a sign.)

Based on the literature it appears that the minimum service life for two major groups of signs is as follows:

- Types I and II — 7 years
- Types III and IV — 10 years.

These values or others that the agency has based on its experience could be used as a replacement threshold in lieu of the actual R_A value.

To implement this option the agency must have a sign dating program whereby each sign is marked in some way with the date the sign was installed. There are a variety of ways to mark the installation date on the sign, such as non-washable ink, embossing and even bar coding. Although as with the first option it would not be necessary to have a sign inventory, this method would be facilitated if the agency did have a sign inventory which included the date when the sign was installed. With a computerized sign inventory, which included date of installation, those signs of a certain age or greater could be identified easily by sorting through the data base.

Within this option the replacement decision would simply be the age of the sign regardless of its retroreflectivity condition. An advantage of this option is that the agency would not have to perform a periodic nighttime inspection for retroreflectivity, relying solely on the age of the sign as a indicator for replacement. However, under this option, the agency may be replacing signs too soon especially if they are using a conservative service life threshold, or conversely, may not be replacing them soon enough if the service life threshold is set too high. Over time as more data becomes available on the effective service life of signs by sheeting material type and/or manufacturer, then this may be less of an issue.

3. Replace Based on Maximum Sign Life With Visual Assessment Verification

The third option is to make a nighttime visual assessment of those signs that have reached or exceeded the maximum service life value used for option 2. Under this option signs would not be replaced until they fail the visual inspection as followed under the first option. In essence this option combines the procedures for options 1 and 2. It is more efficient than either of the two options because it limits the costly nighttime inspection to those signs which are of a certain age and it avoids replacing signs of certain age which may still be effective.

As with options 1 and 2, a computerized inventory is not necessary. However, a computerized inventory, which included the date of sign installation, would greatly facilitate this option. Signs that are a certain age or older could be sorted from the inventory and the list provided to the inspectors.

4. Replace Based on Measured R_A

The third, and most desirable, is to replace the sign when its measured R_A is at or close to the minimum required R_A. For this option it will be necessary for an agency to own or have access to a retroreflectometer, or when it becomes available, the previously discussed mobile SMARTS. Essentially, this option entails the agency to measure those signs suspected of being close to the minimum R_A values. Identification of suspected signs could be through the visual inspection

process, the age of the sign, or, if the computer program being used for the inventory allows, the predicted R_A value based on a retroreflectivity deterioration model. (Currently the FHWA SMS program includes a module that predicts the retroreflectivity level, R_A, for two types of sheeting materials, Type I and IV. This prediction is based on a model developed from research and considers the sheeting color, age, and geographical and environmental factors.)[20]

Again, as with the other options, a sign inventory is not absolutely required, but it is highly desirable. If the sign inventory includes the date of installation, sheeting type, and other key parameters, then signs suspected of being close to the minimum required R_A value can be easily sorted from the data base. Sign inspectors can then be directed to those questionable signs and retroreflectivity readings can be made.

Although this option *may* increase the agency's cost for sign inspection, it should prove to be cost-effective for the overall sign program. The maximum effective service life of the sign would be realized and signs would not be replaced prematurely.

MINIMUM RETROREFLECTIVITY IMPLEMENTATION GUIDELINES

In consideration of the options discussed above, a minimum and desirable program for meeting the minimum retroreflectivity guidelines is recommended. These are discussed below.

Minimum Program

The minimum program consists of the following elements:

1. **Computerized Inventory** — Although it has been stated that it is not necessary to have a computerized inventory, the advantages are such that it is recommended for all agencies, regardless of size. Numerous computer programs exist which can be used off-the-shelf or customized programs can be developed fairly inexpensively. Computers and data base management systems are becoming commonplace and this situation should extend to sign inventory.

   The data elements should be those listed under the **core** and **critical** listing (tables 11 and 12) in the Sign Inventory section. Of particular importance is to have a sign dating program whereby the sign is dated when installed and recorded in the computer inventory.

2. **Inspection** — Inspection of signs for retroreflectivity levels should be done at least annually. (It is emphasized that signs can be deficient for reasons other than poor retroreflectivity and this can and should be identified through normal daytime inspections and maintenance programs.) This can be a simple visual nighttime

inspection. In addition, an agency may obtain a retroreflectometer that can be used either for confirming the adequacy of signs detected by the visual method, and/or just be used at the sign shop in connection in training inspectors and "calibrating" the visual inspection process. Smaller agencies can "share" a retroflectometer (it costs about $3,000) since it is not needed all the time.

Although a "through-the-window-while-driving" nighttime inspection should be performed for all signs, more time could be devoted to signs that are suspected to be deficient. A computerized inventory with sign dating will allow the identification of potentially deficient signs due to age. At these signs, the visual inspection can be augmented by measuring with the retoreflectometer.

3. **Replacement** — The replacement strategy under this program is either based on the inspector's opinion as to the condition of each sign inspected, or, if the retroreflectometer is used, the actual R_A compared to the required R_A.

Desirable Program

The most desirable program is to implement an integrated computerized sign management system. Under such a program nearly all activities related to signing would be integrated through a system of computer modules as was illustrated earlier in figure 2. The key components of the program are described below.

1. **Computerized Inventory** — A computer program would be acquired or developed that would include all the data elements described in the Inventory section. Furthermore, the program would have the capabilities of integrating several components including stockpile inventory, field inventory, inspection histories, work orders, costing and budgeting. It would also have the capability of tracking sign deterioration for the purpose of developing better predictors of sign service life for the different material types. Programs already exist, including the FHWA Sign Management System, that perform many of these functions.

2. **Inspection** — Retroreflectivity inspections would be performed during the day using a hand-held retroreflectometer or, when it becomes available, the mobile traffic sign evaluator. This measurement technique would be only for those signs that are expected to be deficient either because of age or, more preferably, because of an estimated R_A that is derived from a prediction model within the program.

3. **Replacement** — For the purpose of insufficient retroreflectivity condition, signs would be replaced only when they reach the minimum R_A required. (Agencies that prefer to establish higher standards for retroreflectivity can simply increase the minimum requirements.) This is established by comparing the measured value

obtained by either the hand-held retroreflectometer or the Traffic Sign Evaluator against the minimum R_A required for the particular sign.

There are, of course, variations or graduations within these two suggested levels of implementation guidelines. Also, there are specific procedures that each agency will want to adopt to meet their individual needs and existing maintenance procedures.

Agency Level Considerations

Initially it was assumed that the program to be followed for meeting minimum R_A requirements would vary by agency type, that is, State vs. county vs. city vs. town or township. Presumably, the larger the agency, the more sophisticated the program. However, this is not necessarily so. While the amount of funds available for the total sign program in proportion to the number of signs that need to be maintained is certainly a key factor, the most important factor affecting the level of sophistication is the commitment of the personnel who would administer and operate the program. The smallest of agencies can have a fully integrated sign management system for a relatively low cost even considering the need for computer hardware and software and peripheral equipment. On the other hand, State highway departments may find it disproportionally more expensive to implement a full program because of the large network of roads. This situation may also occur with large cities and counties, especially if they have limited budgets for signing. This problem can be overcome, somewhat, if sign management systems are established for separate districts or sections, if appropriate.

The key to the successful implementation of any level of sign management system will, as with all other programs, lie with the commitment and dedication of the staff. This starts with management who provides the tools, direction, and supervision. It continues when there is a person responsible for the continuous operation of the program. And finally, it requires a conscientious sign crew of inspectors and maintenance personnel who understand the merits of the program and ensure that the information they provide is accurate and timely.

APPENDIX A. FHWA SIGN MANAGEMENT SYSTEM (SMS) SUMMARY DESCRIPTION

OVERVIEW OF SMS

The Sign Management System (SMS) has been developed by the Federal Highway Administration (FHWA) Office of Safety and Traffic Operations Research and Development to provide State and local highway agencies with a tool for assembling a sign inventory and to assist them in maintaining their signs in accordance with the anticipated national guidelines on minimum retroreflectivity levels.

To do so, the SMS integrates three basic elements for comprehensive sign management - inventory, inspection and maintenance/replacement. These basic elements help determine the retroreflectivity condition of a sign, which is the key determinant of a sign's effectiveness. To allow for compliance of minimum retroreflective levels, the SMS program estimates when a sign may need replacement based on key data elements such as type of sign, its color, age of sign, etc. The SMS uses initial retroreflectivity (R_A) measurements taken when a sign is installed and a series of deterioration equations to estimate when a sign's retroreflectivity will drop below the minimum guidelines. This way, signs can be scheduled for replacement before their condition becomes substandard.

The SMS program is divided into three sections: Sign Inventory, Sign Dictionary and Utilities.

SIGN INVENTORY

Data Elements

The SMS program requires the identification of certain data elements that are needed for each sign in order to calculate the sign's R_A. Each sign in the inventory is a separate sign record. Each sign record should contain as much information as possible about the sign's age, location, type, manufacturer, color, etc. The data elements are used in the calculation of the R_A and the replacement date. The required data elements are as follows:

- Route name/# — up to 25 characters, where the sign is located.
- Location — three possible methods of measurement (described below).
- Direction — compass direction of travel on the road.
- Position — location of sign relative to the road.

- Orientation — direction the sign is facing.
- MUTCD — codes of sign types.
- Sheeting — type of sheeting used.
- Install date — date of installation of sign.

Several other data elements are not required but can be entered into the sign record to help determine a more accurate R_A level and replacement date.

Location Measurement

There are three methods of sign location measurement available in the SMS. The first type of location measurement is the milepoint location method which may be used if the road is referenced by milepoints. The location of the sign along the road can be entered to the nearest 1/1000 of a mi (0.00161 km). The second type of measurement is the intersection/distance location method. This method may be used to reference the sign location to the nearest intersection or to any other prominent feature (e.g., a bridge). The distance from the intersection is entered in feet. In this location method, the name of the intersection route must be entered in the required "INTERSECT" field. The third location measurement method, the milepost method, may be used when there are markers on the roadside every mile. Distance can be measured to as small as every 0.1 mi (0.161 km). The closest milepost marker to the sign is entered into the record. The distance in feet from the closest milepost marker is recorded with a plus (+) sign for after the milepost marker and a minus (-) sign for before the marker.

History File

A history file is created to track the inspections of each sign record in an inventory file. A history file is specific to the inventory file because it keeps track of all of the inspection data for the signs in that specific file. The sign history file is automatically updated each time a new inspection date for a sign is entered. Additionally, the condition of the sign at the time of inspection can be entered and the measured R_A from field measurements can be recorded. The history file is important in tracking a sign's deterioration through its existence which is used in the Utilities section of the SMS program. It also helps keep track of sign maintenance activity.

Archive Records

An archive file is built when the user creates an active inventory file. Each active file contains all of the current active sign records. An archive file is a storage file used when active signs are removed from service. To archive a record, the user moves it from the active file to the archive file. All of the data previously entered into the active sign record will remain as it is in

the archive file because archive files may be accessed, but cannot be modified. An archive record stores the removal date and reason for the removal of the sign.

UTILITIES

Test Sign Program

The purpose of the Test Sign Program within the SMS is to refine deterioration equations so that the equations better model the conditions in a particular geographic area. The user is able to tag sample signs for testing, and track their retroreflectivity levels over several years. These levels are then input into the SMS and are used to develop a specific set of equations relative to the geographic area for the test signs. The SMS program default equations would not be used to determine deterioration rates in the test sign program. Rather, a predictive set of equations using conditions related to the geographic area would be utilized. Therefore, more accurate results could be determined for the test signs as well as the remainder of the sign inventory. In this way, the test sign program will permit users to more accurately predict sign service life and replacement needs in their specific geographic location.

There are six essential activities involved in the test sign program:

- Sign selection — The program needs to include a large enough selection of test signs to make the sample statistically accurate.
- Identification of signs in the SMS — Tag signs picked for the test program so they can be tracked.
- Periodic measurements of sign retroreflectivity — Conduct periodic measurements of the test signs' R_A using either a hand-held retroreflectometer or a traffic sign evaluator. Readings will be averaged by the SMS to yield a single background reading and single legend reading.
- Data analysis — Test sign data should be analyzed for consistency.
- Modification of equations — Deterioration equations in the SMS program can be modified with the results of the test sign program.
- Verification of results — Accuracy of updated equations can be tested by inspection of the available R_A of non-test signs in the inventory.

R_A Measurements and Calculation of Sign Results

The R_A is the measure of a sign's retroreflectivity level. As a sign ages, its retroreflectivity deteriorates more and more causing the sign to become increasingly difficult to

read. The SMS has the ability to estimate when a sign may need to be replaced based on the comparison of different R_A measurements. FHWA has developed minimum retroreflectivity standards which have been programmed into the SMS as the required R_A. The required R_A considers elements such as sign background color, legend color, sign size and roadway speed in its calculations.

A second type of R_A measurement is calculated from the SMS programs and equations by using data from the sign inventory database. Estimates of available R_A are prepared using data elements, such as the sign type, sign color, age of sign, and sheeting material of the sign, which are entered into each individual sign record. Additionally, the SMS equations use the amount of heating degree days, the annual precipitation and the elevation appropriate to the region, which must be entered into the system to allow it to calculate the available R_A. The SMS does not require field measurements to calculate available R_A, rather the SMS calculates the R_A from the data in each sign record. The SMS compares a sign's available R_A to the required R_A and determines the remaining retroreflectivity of the sign to calculate the sign's remaining service life. From this, the replacement date is determined by adding the remaining service life to the current date. The maximum life of a sign has been established as 20 years, regardless of the replacement date calculated.

Deterioration Model for EG and HP Sign Types

The capability of predicting the replacement date of a sign is limited to signs made of sheeting Type I (engineering grade) and sheeting Type IV (high-intensity). There are eight possible sheeting/color combinations derived from four possible sign colors (red, yellow, green and white) and the two sheeting types. Depending upon the color and sheeting combination, the SMS calculates the deterioration rate of the sign using the regression equation for that particular combination. These equations are only used to estimate the available R_A. From this calculation, the SMS can estimate the proper replacement date for the sign.

SIGN DICTIONARY

The Sign Dictionary contains the information of all of the signs in the Manual on Uniform Traffic Control Devices (MUTCD). These signs are referenced from the sign inventory records. The sign dictionary accepts custom signs from a particular jurisdiction.

Cost Estimator

Most of the sign records in the MUTCD sign dictionary provide replacement costs per square foot for each particular sign. In the case when the replacement cost is not provided for a sign, a user may enter a particular screen to enter or modify an average cost per square foot for sign replacement materials. Each sign record will have its own replacement costs associated with it depending upon the type of sign, and the type of sheeting and backing of the sign. A sign inventory report summarizes all of the costs for each sign in the entire inventory file.

REFERENCES

1. *Manual on Uniform Traffic Control Devices.* Federal Highway Administration, U.S. Department of Transportation, Washington, DC. 1988.

2. *ASTM Standards on Color and Appearance Measurement*, American Society for Testing and Materials, Philadelphia, Pennsylvania, Fourth Edition 1994.

3. *Standard Specification for Construction of Roads and Bridges on Federal Highway Project, FP-96.* U.S. Department of Transportation, Federal Highway Administration. 1992.

4. Paniati, J.R. and Mace, D.J. "Minimum Retroreflectivity Requirements for Traffic Signs" Report No. FHWA-RD-93-077. Federal Highway Administration. 1996.

5. Warne, Richard C. "Risk Management Premium Modifier Program." Utah Risk Management Mutual Association, Orem, Utah. August 1992.

6. Baker, William and Blessing, William "Highway Location Reference Methods." NCHRP Synthesis 21, Transportation Research Board, National Research Council, Washington, DC. 1974.

7. "Sign Management System User Guide", Federal Highway Administration, Department of Transportation, Washington, DC. 1995.

8. Kuennen, Tom "New Sign System Matches Images, Data." *Roads and Bridges*, Vol. 30, No. 3, Des Plaines, Illinois. March 1992.

9. Poling, Allen; Lee, Jim; Gregerson, Patrick; and Handley, Paul. "Comparison of Two Sign Inventory Data Collection Techniques for GIS." TRB Preprint 940404, 1994 Transportation Research Board Annual Meeting, Washington, DC. January 1994.

10. Cipolloni, Mark J. "Using GIS to Better Manage Existing Transportation Facilities." *Compendium of Technical Papers, 1993 Annual Meeting*, Institute of Transportation Engineers. The Hauge, Netherlands, September 1993.

11. Hughes, Warren E.; Reinfurt, Donald; Yohanan, David; Rouchon, Margaret, and McGee, Hugh W. "New and Emerging Technologies for Improved Accident Data Collection." Publication No. FHWA-RD-92-097. Federal Highway Administration, U.S. Department of Transportation, McLean, Virginia. March 1993.

12. Hyman, William A.; Horn, Ancel D.; Jennings, Omar; Hejl, Federick; and Alexander. Timothy. "Improvements in Data Acquisition Technology for Maintenance Management

Systems." NCHRP Report 334. Transportation Research Board, National Research Council, Washington, DC. December 1990.

13. Hanley, Richard C. "Development of the Connecticut Department of Transportation Videodisc-based Sign Inventory System." Report No. 1345-F-94-1. Bureau of Engineering and Highway Operations, Connecticut Department of Transportation, Newington, Connecticut. March 1994.

14. Datta, Tapan K., and Herf, Lynne. "Cost-Effectiveness Analysis for Various Inventory Procedures." *ITE Journal*, Vol. 56, No. 9. Institute of Transportation Engineers, Washington, DC. September 1986.

15. Jacobs, Mark J., "City of Issaquah Traffic Sign Inventory Final Report." Transportation Planning and Engineering, Inc. Bellevue, Washington. October 1991.

16. Personal conversation with Dwight Cooke, Minnesota Department of Transportation. March 1993.

17. Cunnard, Richard A. "Maintenance Management of Street and Highway Signs." NCHRP Report 157. Transportation Research Board, National Research Council, Washington, DC. September 1990.

18. *Traffic Sign Handbook.* Institute of Transportation Engineers. Washington DC. (In Press).

19. Kenyon, W. D., et al. "Maintenance of Reflective Signs," FHWA-NY-RR-82-11, Federal Highway Administration, Washington DC. 1982.

20. Black, K. L., McGee, H. W., Hussain, S. F., and Rennilson, J. J. "Service Life of Retroreflective Traffic Signs," Report No. FHWA-RD-90-091, Federal Highway Administration, Washington DC. October 1991.

21. Lagergren, E., "Traffic Sign Retroreflectivity Measurements Using Human Observers." Washington State Department of Transportation, WA-RD 1401.1, 1987.

22. *Nighttime Inspection Guide for Traffic Sign Retroreflectivity* (being prepared).

APPENDIX F

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)

RAISED PAVEMENT MARKER REFLECTIVITY

By

V. J. Pezoldt
Rodger J. Koppa
Richard A. Zimmer
A.T. Perry II
and
Helene W. Milsap

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

Sponsored by

Texas State Department of Highways and Public Transportation

September 1990

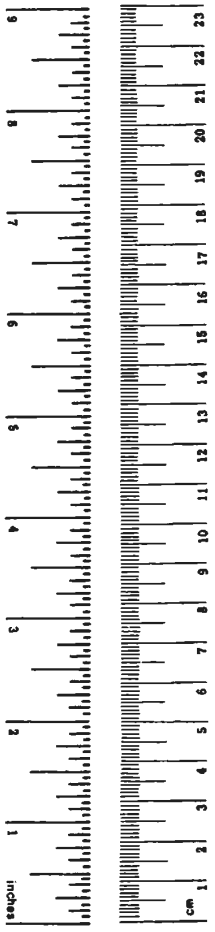
TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843

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

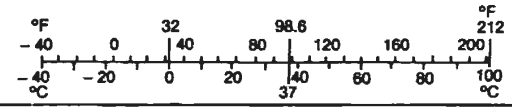
* SI is the symbol for the International System of Measurements

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.

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.

TABLE OF CONTENTS

PAGE

1. INTRODUCTION 1

Background of Project 1
Project Objectives 1
Organization of the Report 2

2. PHOTOMETRIC ASSESSMENT OF RAISED PAVEMENT MARKERS . . 5

TTI Laboratory Measurement 5
Photometric Assessment at SDHPT 5
Field Measurement 9

3. DEVELOPMENT OF A MOBILE RAISED PAVEMENT MARKER MEASUREMENT SYSTEM 11

Introduction 11
Design Requirements 11
Video System 12
Infrared Modulated Beam System 14
System Costs and Cost Effectiveness 17
Conclusions 20

4. THRESHOLD STUDIES 23

Threshold Study 1: Threshold Specific Intensities of Retroreflective Raised Pavement Markers 23
Purpose and Objectives 23
Ground Rules and Assumptions 23
Test Site Description 24
Research Participants 25
Test Design and Procedures 27
Results 29

Threshold Study 2: An Analysis of Threshold Specific Intensities to Account for Rain Diffusion 34

Threshold Study 3: Thresholds for Detection of Retroreflective Raised Pavement Markers under Simulated Wet Weather Conditions 39
Introduction 39
Method 39
Results 43
Summary of Findings 47

5. RAISED PAVEMENT MARKER DURABILITY 55

Types of Pavement Markers Used in Texas 55
Assessment of In-Service RPMs 57

TABLE OF CONTENTS

PAGE

Thermal Stress Study 1: The Effect of Thermal Stress on the Photometric Performance of Retroreflective Raised Pavement Markers 61
Introduction 61
Method 61
Results 62
Discussion 66

Thermal Stress Study 2: Thermal Shock from RPM Adhesive 59 68
Introduction 68
Method 68
Results 69

Abrasion Studies 71
Abrasion Study 1: Laboratory Abrasion of RPMs . 71
Abrasion Study 2: The Effect of Tire Impacts on RPM Photometric 76
Conclusions 82

6. FEASIBILITY OF RPM RESTORATION 87

Method 87
Results and Discussion 88

7. RAISED RETROREFLECTIVE PAVEMENT MARKER PURCHASING TRENDS IN OTHER STATES 91

California 91
Florida 91
Georgia 91

8. CONCLUSIONS AND RECOMMENDATIONS 93

Conclusions 93
Recommendations 95

9. REFERENCES 97

APPENDIX A TTI Photometric Laboratory Procedure 99

APPENDIX B Statistical Summary Tables 102

LIST OF TABLES

PAGE

TABLE 1-1. Guide to locating specific project information 3

TABLE 2-1. Comparison of RPM photometric assessment by the SDHPT and TTI laboratories 6

TABLE 2-2. Comparison of RPM photometric assessment by the SDHPT and TTI laboratories with adjustment to D-9 values 8

TABLE 4-1. Specific Intensity of threshold study RPM specimens 24

TABLE 4-2. Threshold study research participants 27

TABLE 4-3. Summary of results: Percent of RPMs detected as a function of color, specific intensity, and viewing condition 30

TABLE 4-4. Predicted specific intensity thresholds for 80-year-old drivers, RPMs illuminated by 20,000 candela headlamps 32

TABLE 4-5. Predicted specific intensity thresholds for 80-year-old drivers under clear and rainy conditions, RPMs illuminated by 20,000 candela headlamps 37

TABLE 4-6. Study 3 research participants 42

TABLE 4-7. Test setup from observer vehicle (daylight) . 45

TABLE 4-8. Test setup from observer vehicle (night) . . 48

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 49

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 50

TABLE 5-1. RPMs used on Texas highways 56

LIST OF TABLES

PAGE

TABLE 5-2. Mean percent change in SI after heat treating as a function of RPM type 63

TABLE 5-3. Mean percent change in SI after heat treating as a function of heat cycle 63

TABLE 5-4. Mean percent change in SI after cold treating as a function of cold cycle 65

TABLE 5-5. Mean percent change in SI after cold treating as a function of RPM type 66

TABLE 5-6. Tukey's Studentized Range (HSD) Test for variable: SI 70

TABLE 5-7. Specific intensity as a function of RPM type and period 70

TABLE 5-8. Tire impact study test RPMs 76

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). . . . 78

TABLE 5-10. Average percent change in SI over all tire impacts as a function of RPM model 79

TABLE 5-11. Average SI over all RPM models as a function of number of tire impacts 79

TABLE 5-12. Average SI over all tire impacts as a function of RPM model 80

TABLE 6-1. Mean specific intensity of restoration test RPMs 88

LIST OF FIGURES

PAGE

FIGURE 3-1. Video-based field measurement system 13

FIGURE 3-2. Block diagram of prototype infrared field measurement device 15

FIGURE 3-3. Configuration of installed infrared field measurement device 17

FIGURE 3-4. Schematic of infrared field measuring device (1) 18

FIGURE 3-5. Schematic of infrared mobile field measurement measurement device (2) 19

FIGURE 4-1. Urban environment visual scene 26

FIGURE 4-2. Testing procedure and instructions 28

FIGURE 4-3. Test observer vehicle 40

FIGURE 4-4. Shutter apparatus for presenting RPMs . . . 40

FIGURE 4-5. Rear view of shutter apparatus 41

FIGURE 4-6. "Opposing traffic" vehicle 41

FIGURE 4-7. Test setup from observer vehicle (daylight) 44

FIGURE 4-8. Test setup from observer vehicle (night) . . 44

FIGURE 4-9. Predicted Threshold SI, Adapting conditions for observer: Opposing traffic, wet pavement 51

FIGURE 4-10. Predicted Threshold SI, Adapting conditions for observer: Dark highway, no ambient lighting 52

FIGURE 4-11. Predicted Threshold SI, Adapting conditions for observer: Urban corridor, No opposing traffic 53

FIGURE 5-1. Typical RPM life cycle, plastic-faced Model 88 58

FIGURE 5-2. Dry and wet measurements of Model 88 RPMs . 59

FIGURE 5-3. Dry and wet measurements of Model 911 RPMs . 60

LIST OF FIGURES

PAGE

FIGURE 5-4. Change in SI as a function of RPM type and cycle 64

FIGURE 5-5. Change in SI as a function of RPM type and cycle 67

FIGURE 5-6. SI before and after thermal shock from adhesive 69

FIGURE 5-7. Photograph of abrading element of laboratory abrasion box 73

FIGURE 5-8. Photograph of laboratory RPM abrasion box . 73

FIGURE 5-9. SI of laboratory-abraded glass and plastic RPMs 74

FIGURE 5-10. Photomicrograph of a plastic-faced Model 88 RPM subjected to 10 abrader passes 75

FIGURE 5-11. Photomicrograph of a glass-faced Model 911 RPM subjected to 10 abrader passes 75

FIGURE 5-12. SI % change as a function of RPM type and impacts 81

FIGURE 5-13. SI as a function of RPM type and impacts . . 81

FIGURE 5-14. Photograph of plastic-faced Model 88 RPM (ID #28) after 4400 tire impacts 83

FIGURE 5-15. Photomicrograph of plastic-faced Model 88 RPM (ID #28) after 4400 tire impacts 83

FIGURE 5-16. Photograph of glass-faced Model 911 RPM (ID #37) after 4400 tire impacts 84

FIGURE 5-17. Photomicrograph of glass-faced Model 911 RPM (ID #37) after 4400 tire impacts 84

FIGURE 6-1. SI of new, abraded, and restored Model 88 RPMs 89

FIGURE 6-2. SI of weathered and tire impacted restored RPMs 90

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

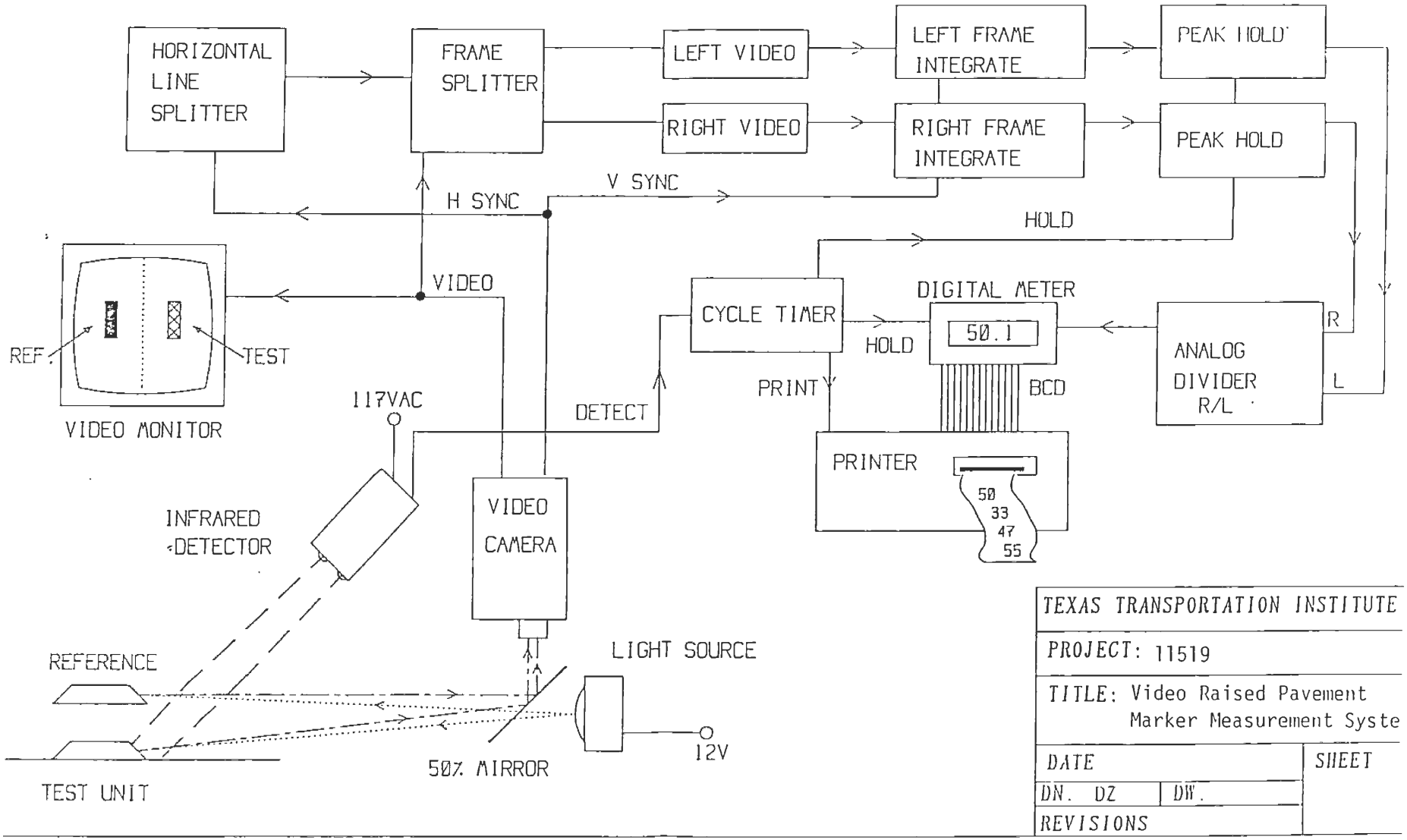


Figure 3-1. Video-based field measurement system

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

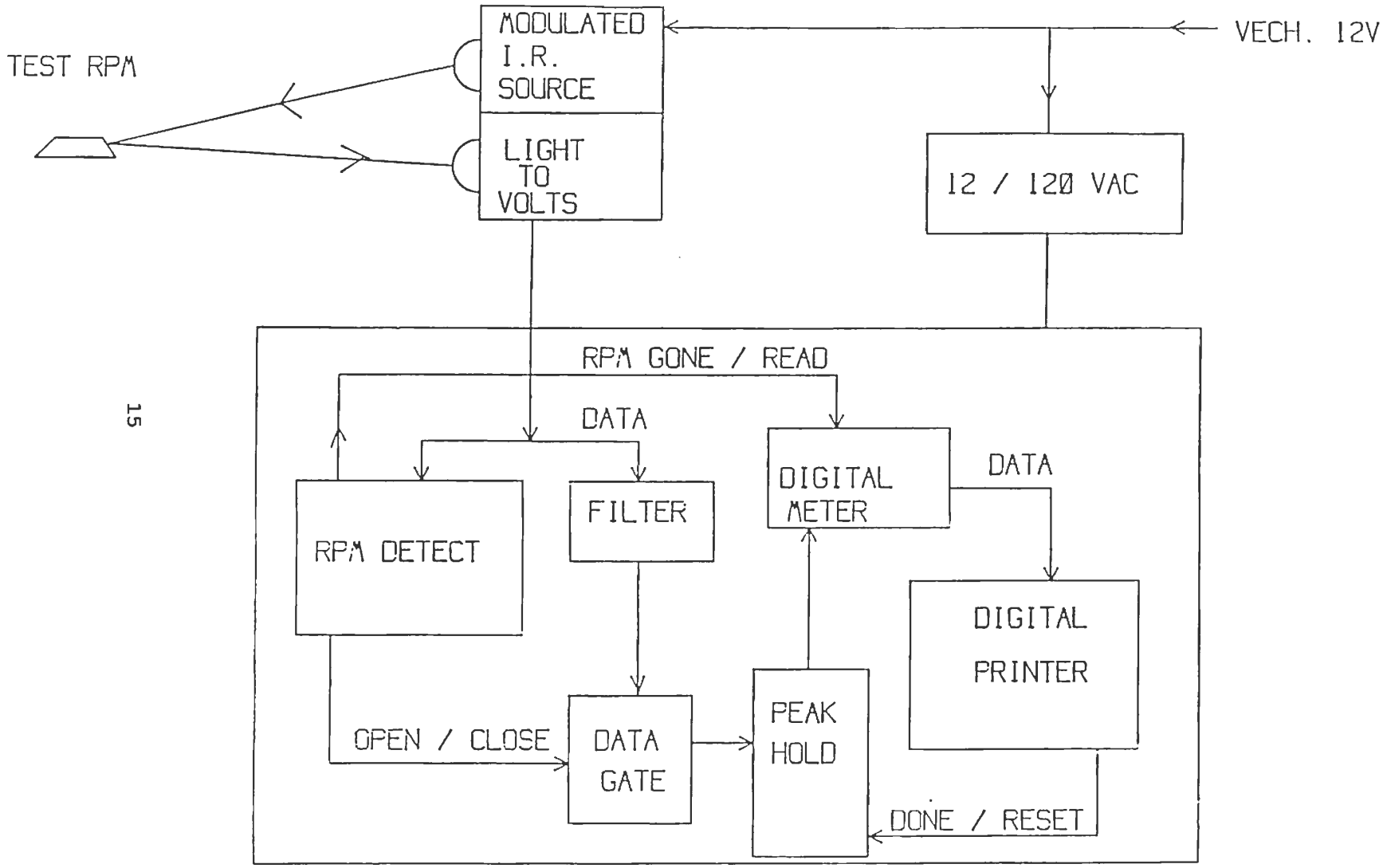


Figure 3-2. Block diagram of prototype infrared field measurement device

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

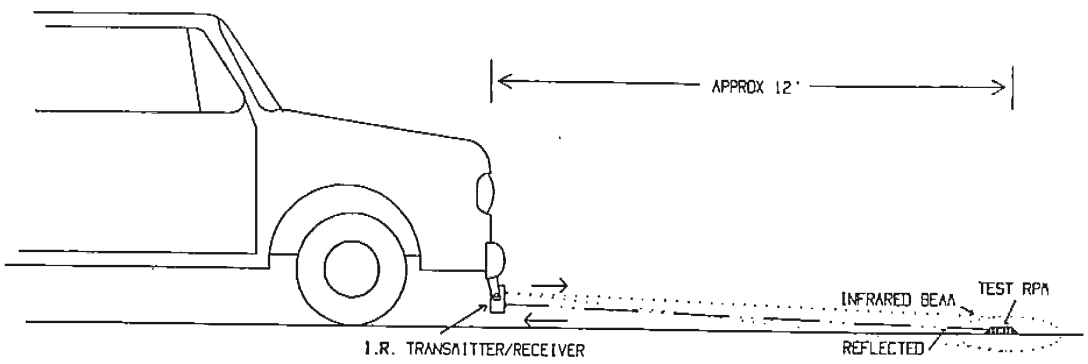


Figure 3-3. Configuration of installed infrared field measurement device.

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.

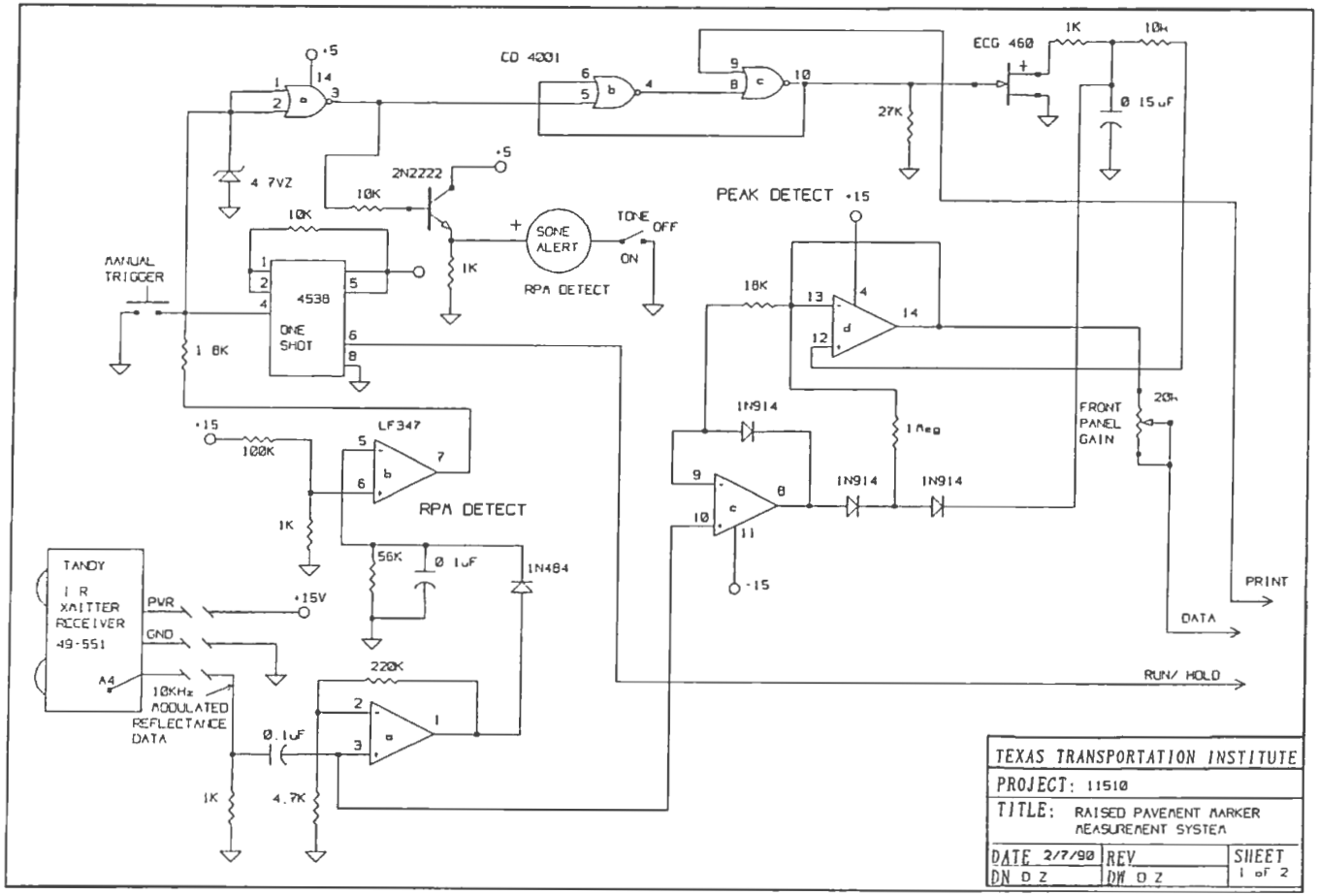


Figure 3-4. Schematic of infrared field measuring device (1).

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.

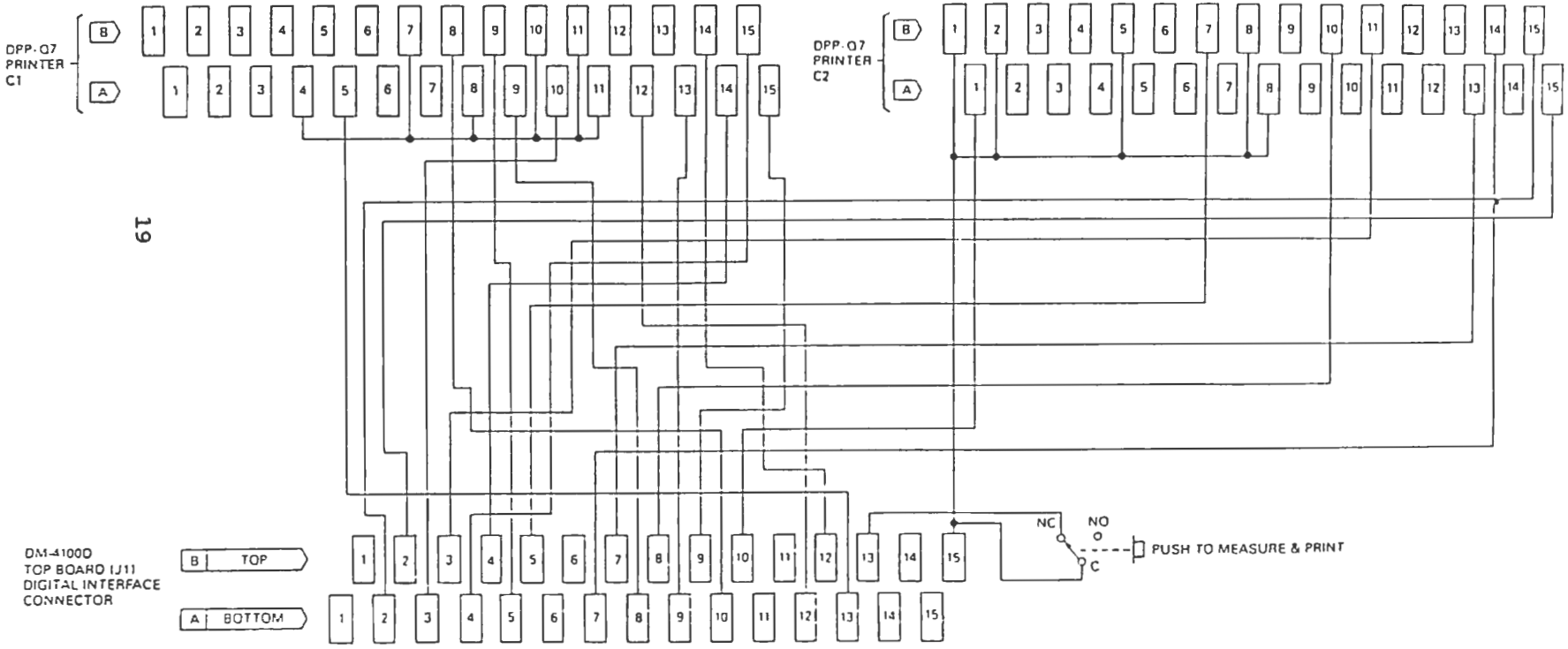


Figure 3-5. Schematic of infrared mobile field measurement device (2).

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-

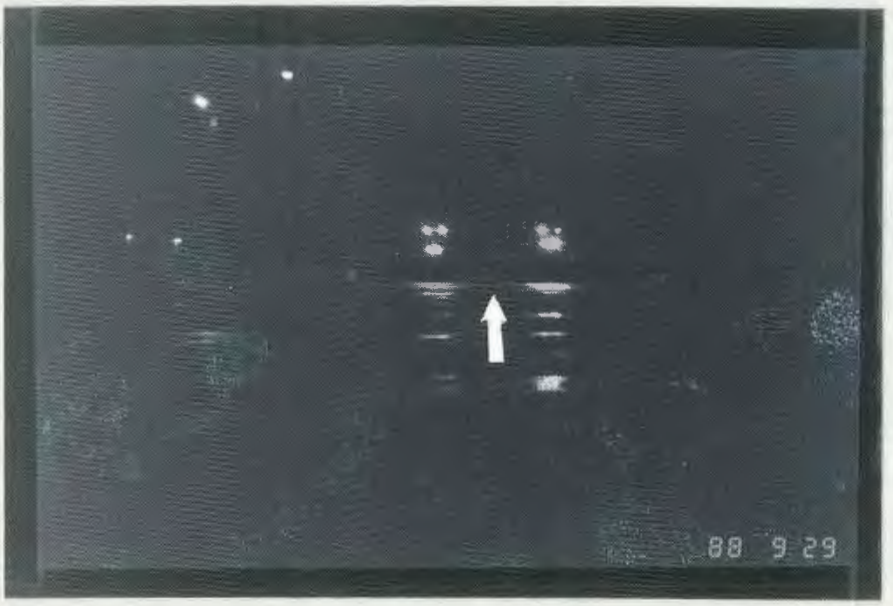


Figure 4-1. Urban environment visual scene.
(Arrow indicates faintly visible target RPM)

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.

"Rural" (Dark) Conditions

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

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 (Clear)	Transmissivity of Rainfall 0.5*	1.0*	2.0*	Illuminance of Headlamps 0.5*	1.0*	2.0*	Luminance of RPM Req'd to See 0.5*	1.0*	2.0*	Threshold RPM SI in Rain 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 (Clear)	Transmissivity of Rainfall 0.5*	1.0*	2.0*	Illuminance of Headlamps 0.5*	1.0*	2.0*	Luminance of RPM Req'd to See 0.5*	1.0*	2.0*	Threshold RPM SI in Rain 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 0.5*	1.0*	2.0*	Illuminance of Headlamps 0.5*	1.0*	2.0*	Luminance of RPM Req'd to See 0.5*	1.0*	2.0*	Threshold RPM SI in Rain 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 0.5*	1.0*	2.0*	Illuminance of Headlamps 0.5*	1.0*	2.0*	Luminance of RPM Req'd to See 0.5*	1.0*	2.0*	Threshold RPM SI in Rain 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.

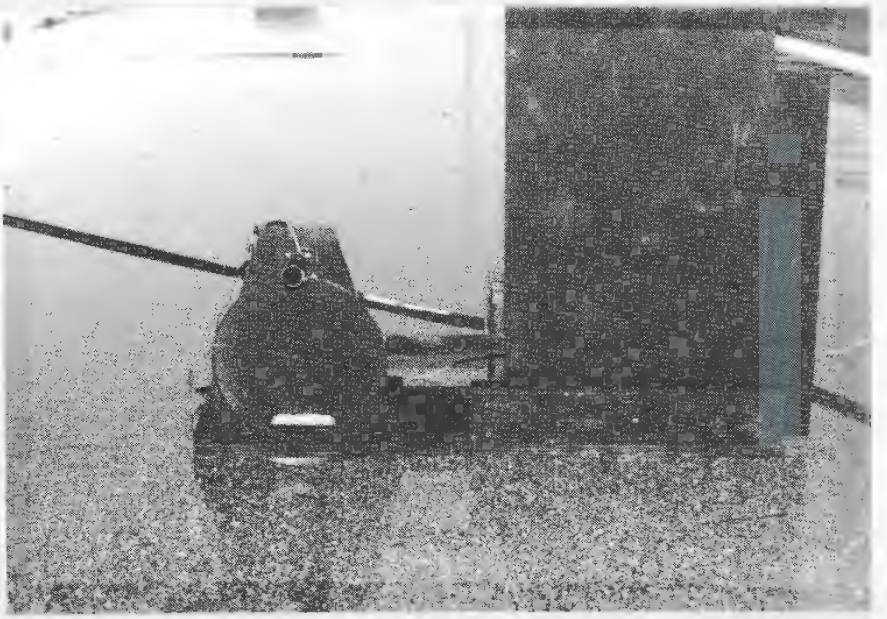


Figure 4-4. Shutter apparatus for presenting RPMs

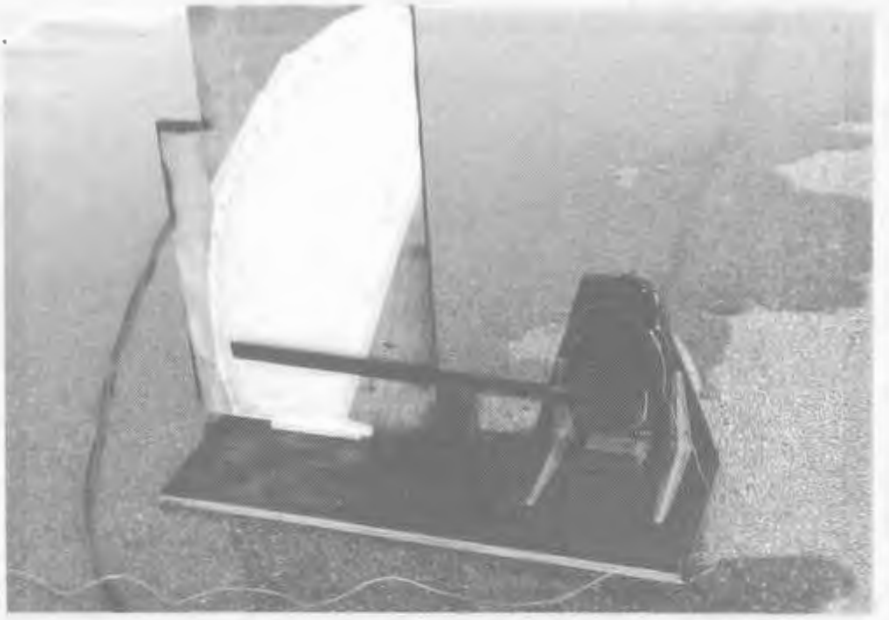


Figure 4-5. Rear view of shutter apparatus



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.

Estimate of Minimum Acceptable Illuminance at Eye from RPM

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.

	RPM Color		
Subject	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)	Rainfall Rate: Clear	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)	Rainfall Rate: Clear	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			

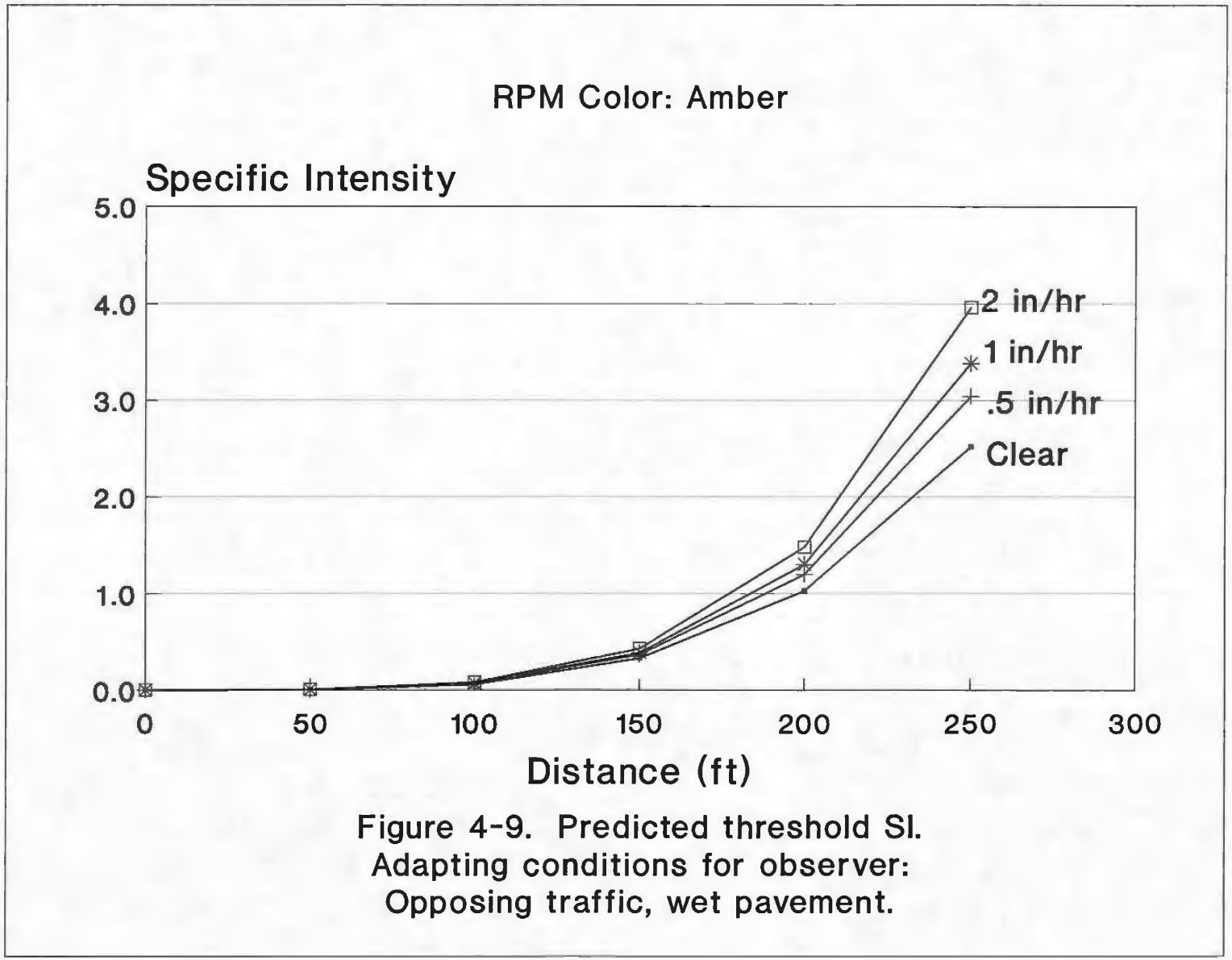


Figure 4-9. Predicted threshold SI. Adapting conditions for observer: Opposing traffic, wet pavement.

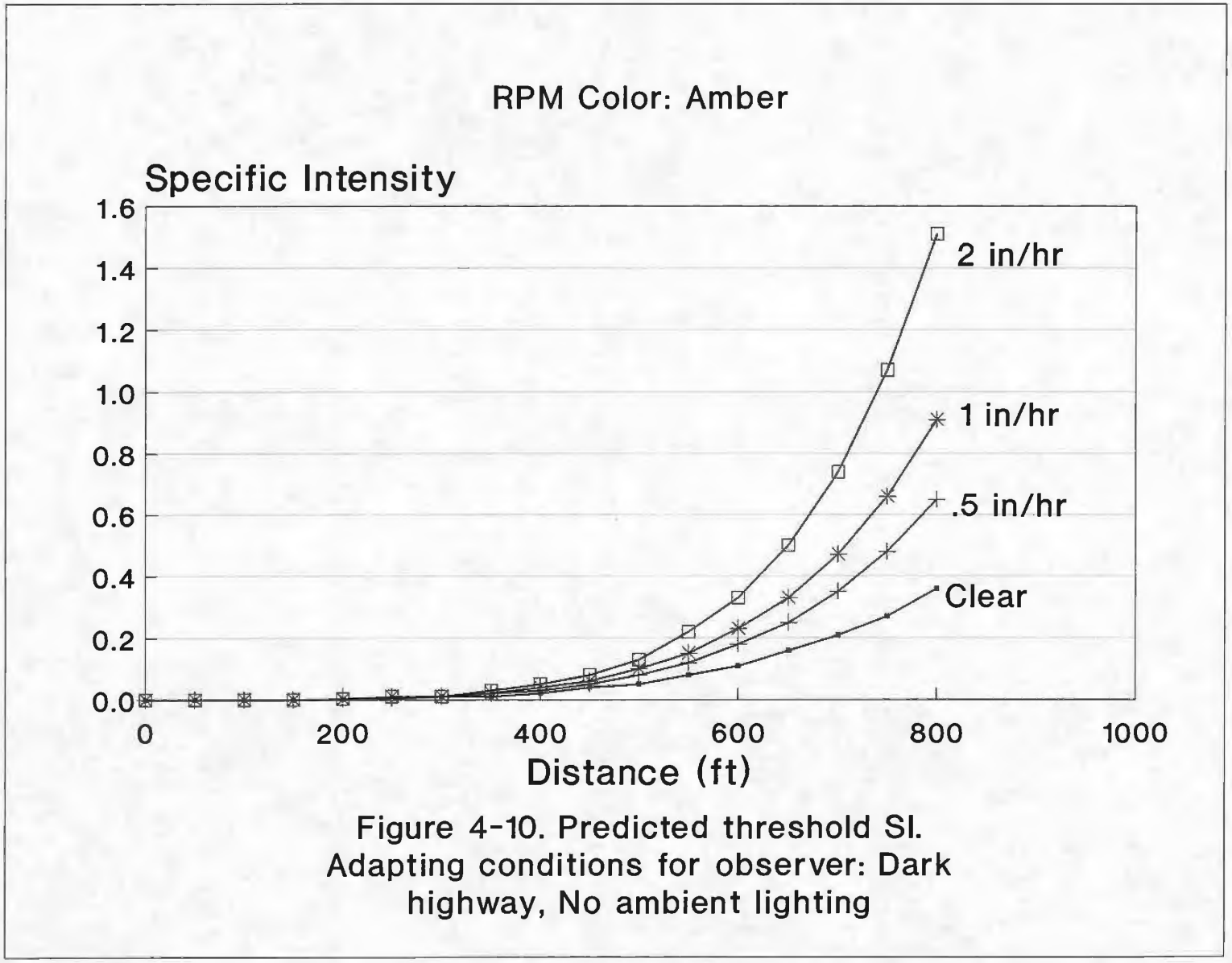


Figure 4-10. Predicted threshold SI. Adapting conditions for observer: Dark highway, No ambient lighting

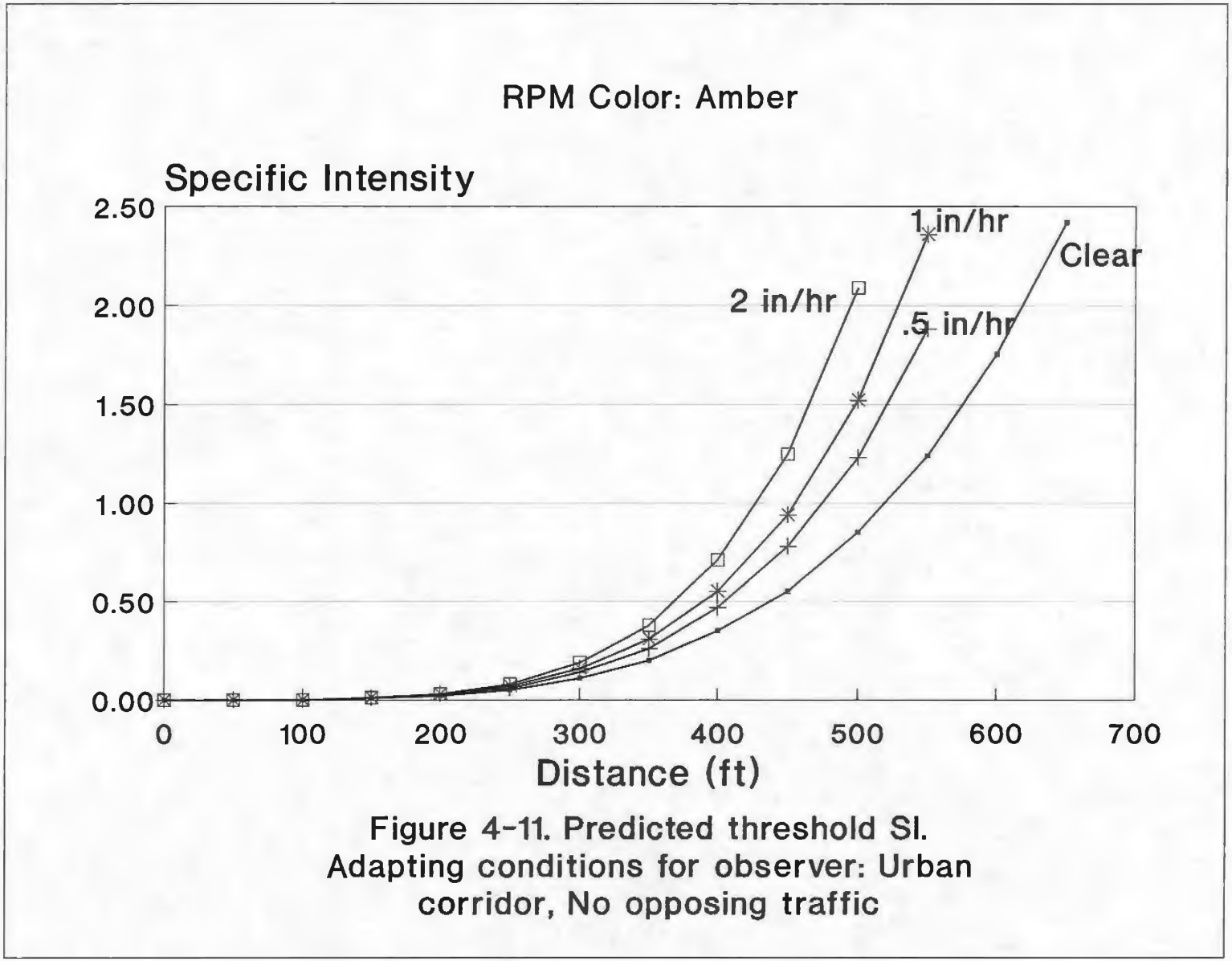


Figure 4-11. Predicted threshold SI. Adapting conditions for observer: Urban corridor, No opposing traffic

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, Stimsonite, manufactured by a division of the Amerace Corporation and Ray-O-Lite, 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

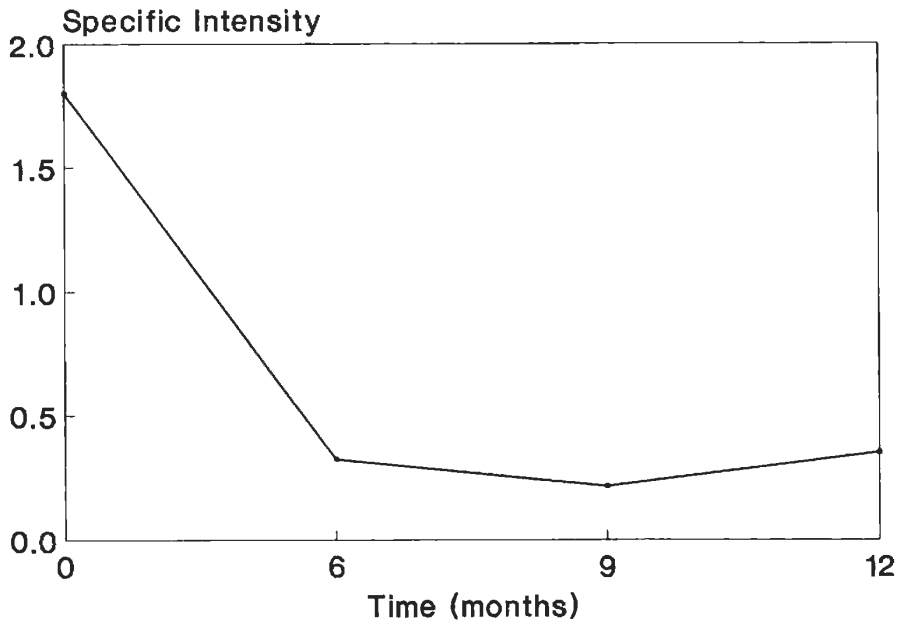


Figure 5-1. Typical RPM life cycle, plastic-faced Model 88.

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

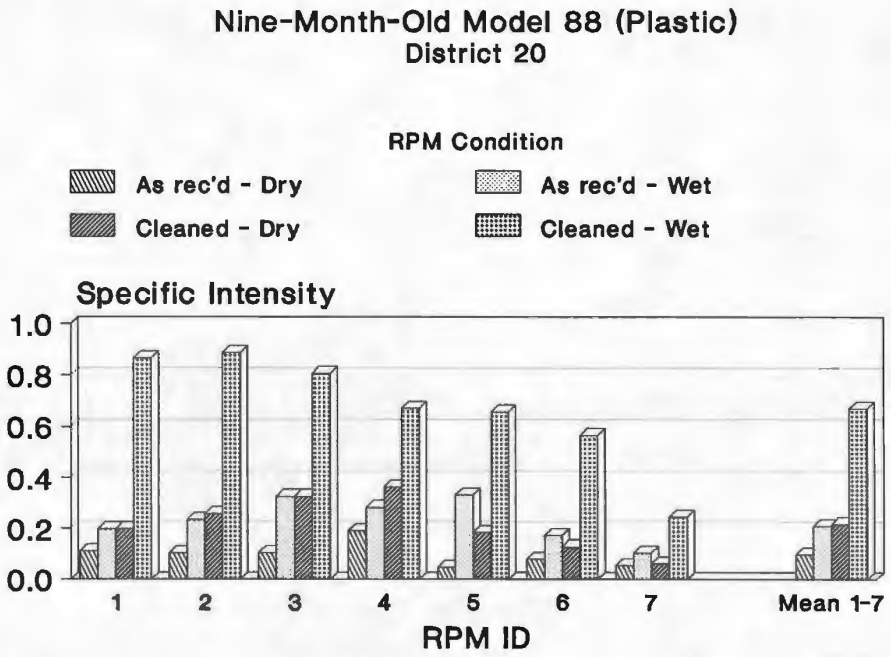


Figure 5-2. Dry and wet measurements of Model 88 RPMs.

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.

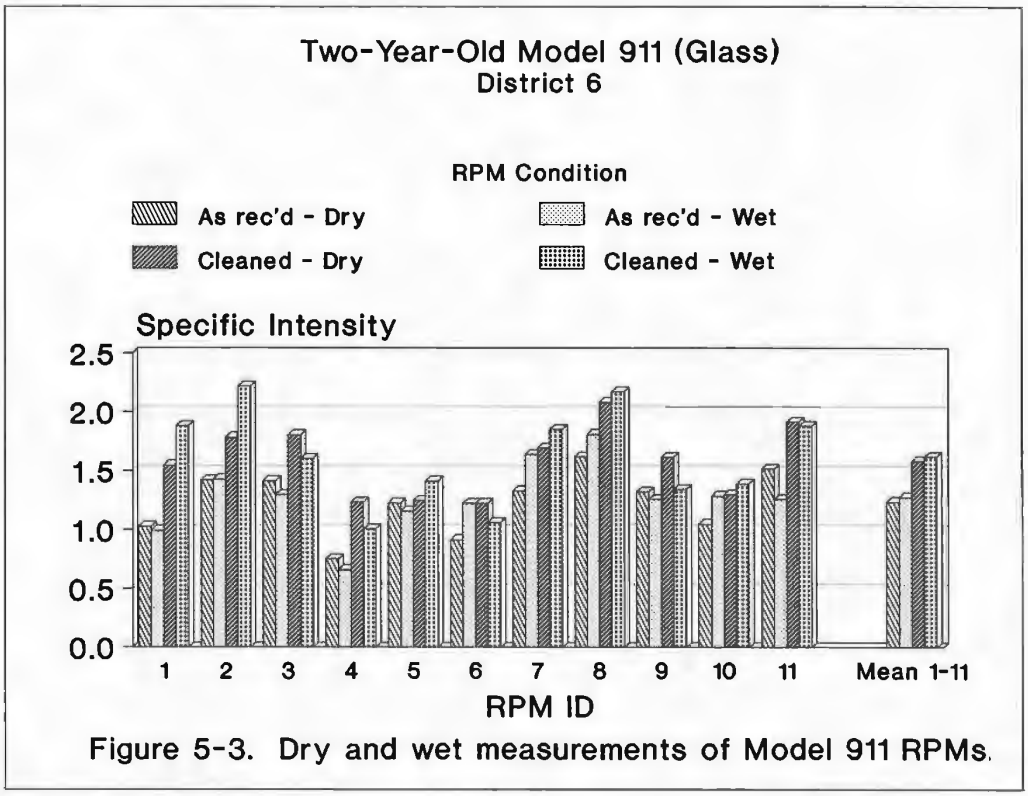


Figure 5-3. Dry and wet measurements of Model 911 RPMs.

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.

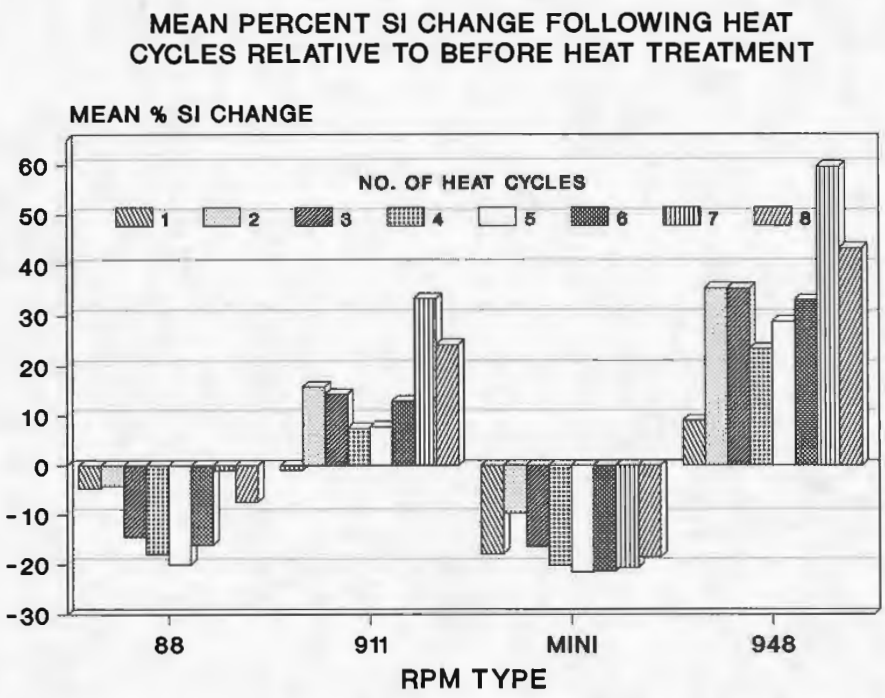


Figure 5-4. Change in SI as a function of RPM type and cycle

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.

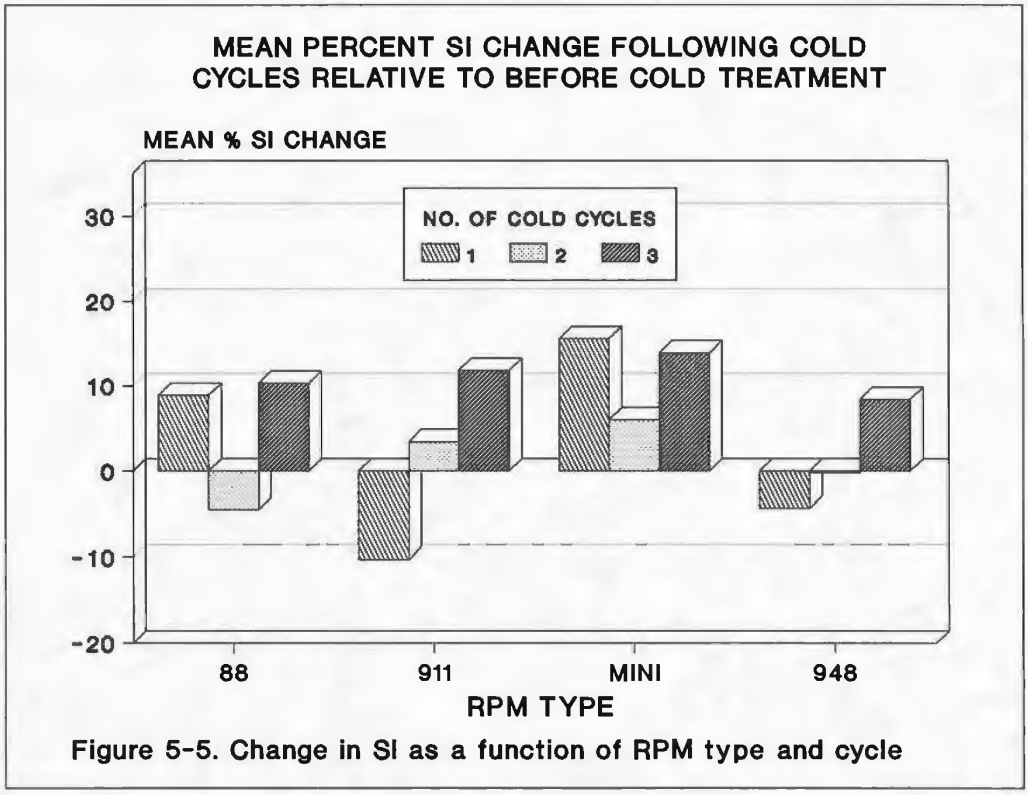


Figure 5-5. Change in SI as a function of RPM type and cycle

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.

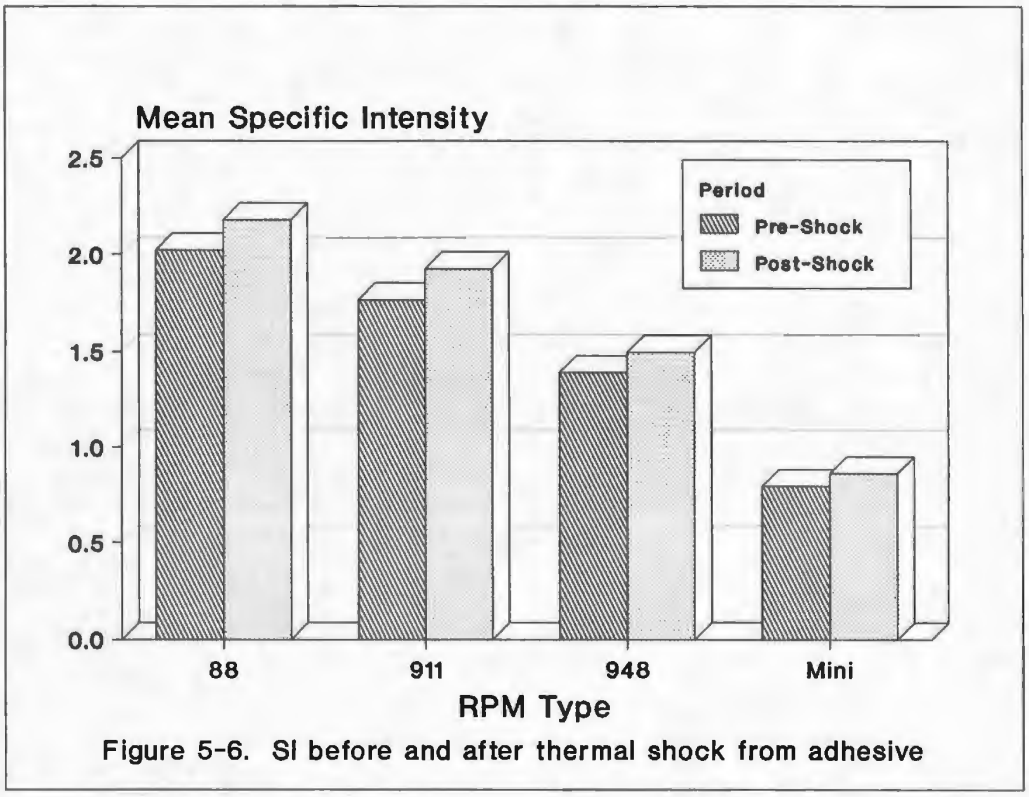


Figure 5-6. SI before and after thermal shock from adhesive

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 increase 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.

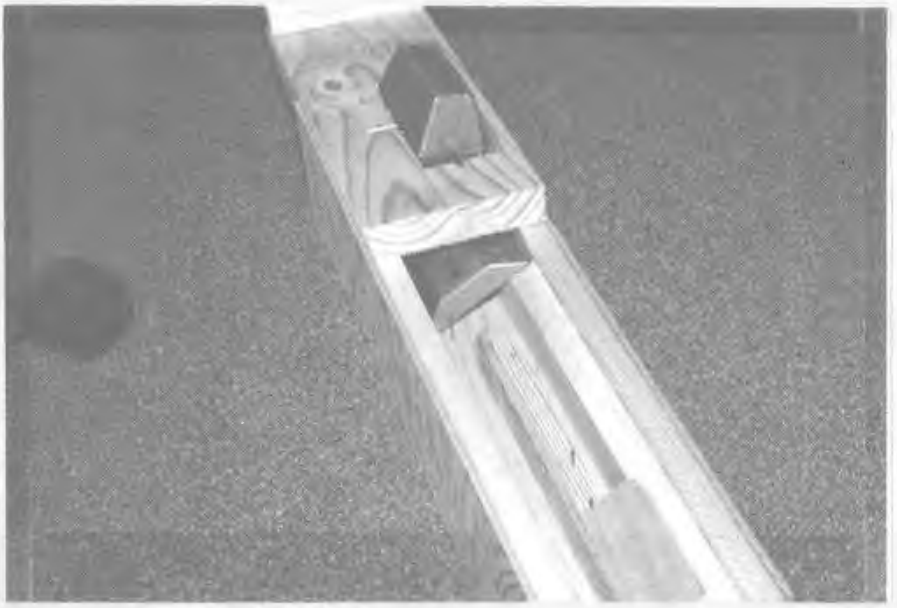


Figure 5-8. Photograph of laboratory RPM abrasion box.

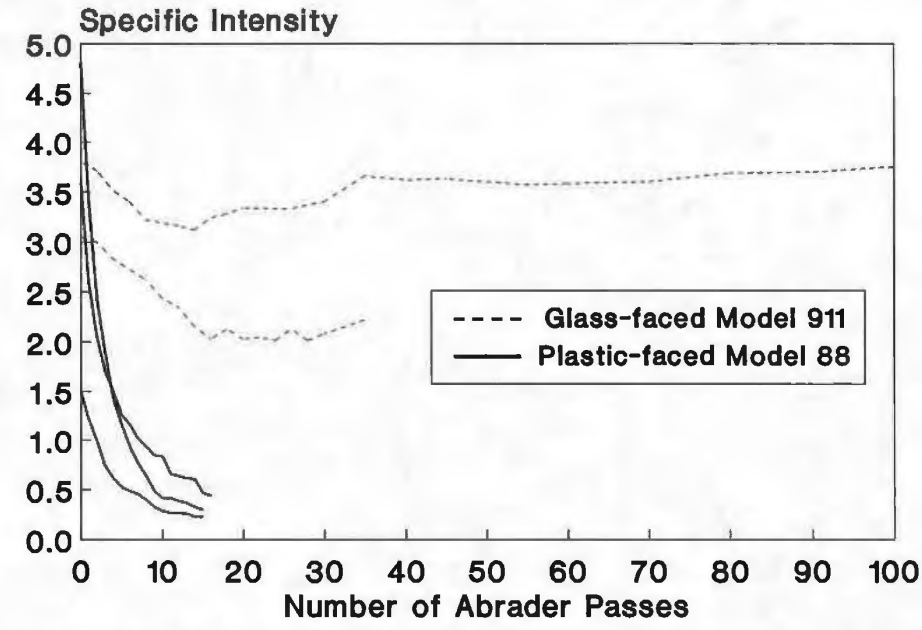


Figure 5-9. SI of laboratory-abraded glass and plastic RPMs

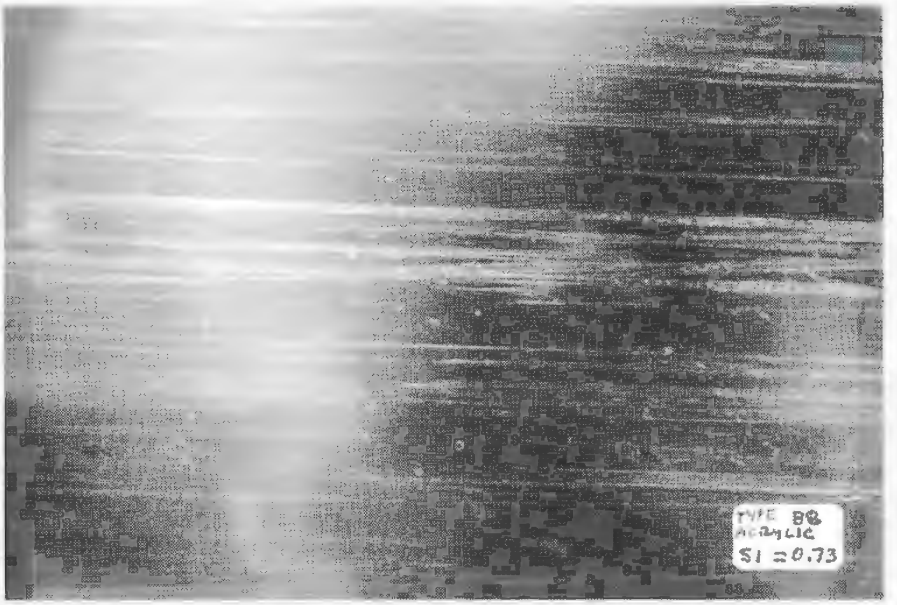


Figure 5-10. Photomicrograph of a plastic-faced Model 88 RPM subjected to 10 abrader passes.

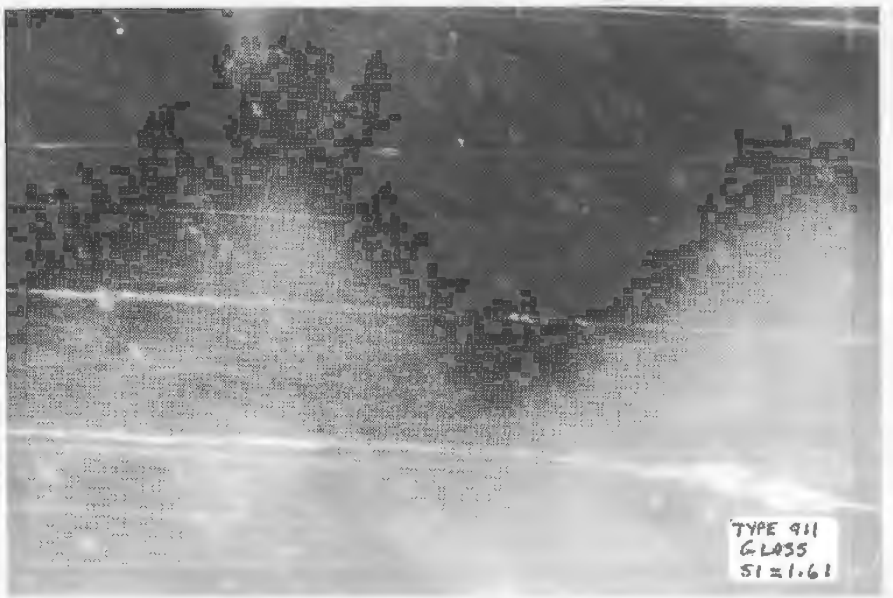


Figure 5-11. Photomicrograph of a glass-faced Model 911 RPM subjected to 10 abrader passes.

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 increased 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

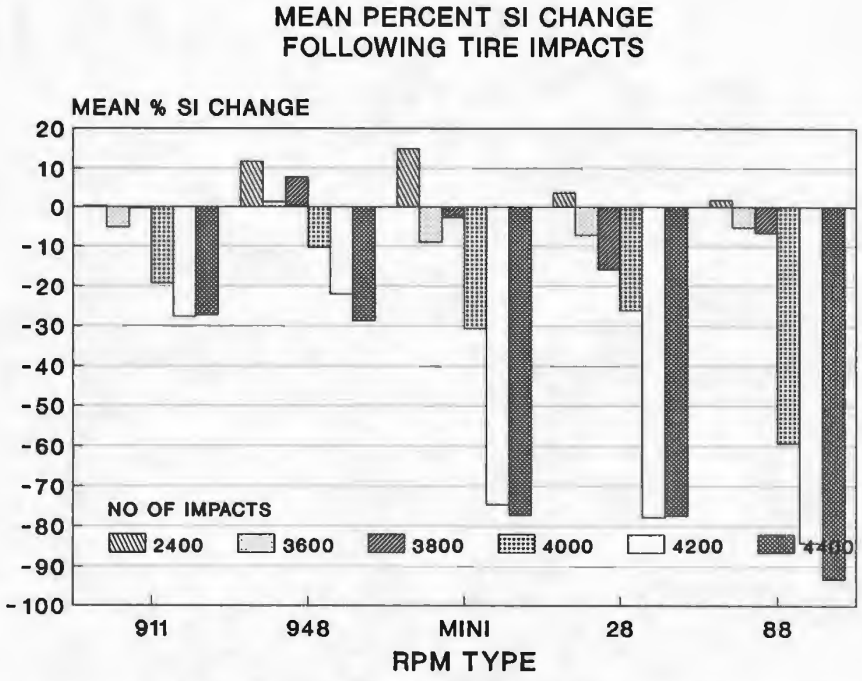


Fig. 5-12. SI % change as a function of RPM type and impacts

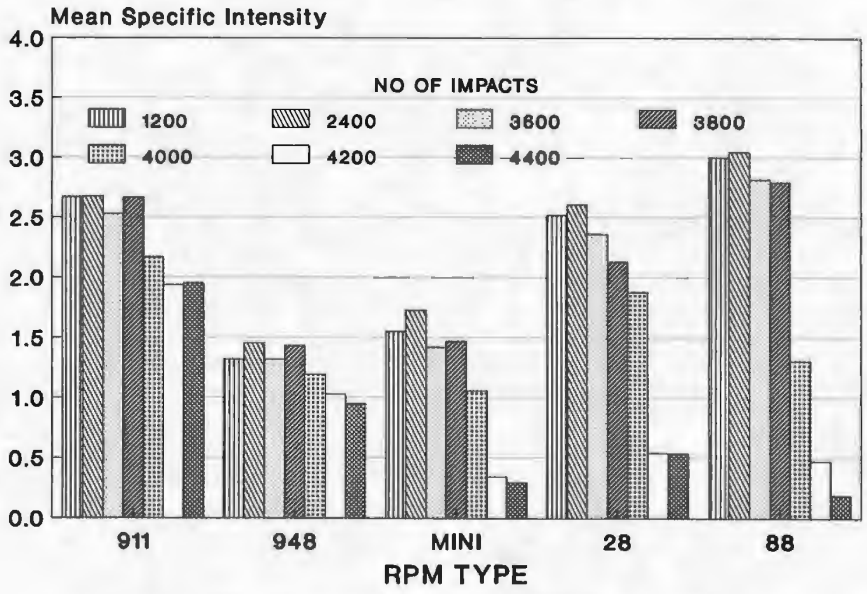


Figure 5-13. SI as a function of RPM type and impacts

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

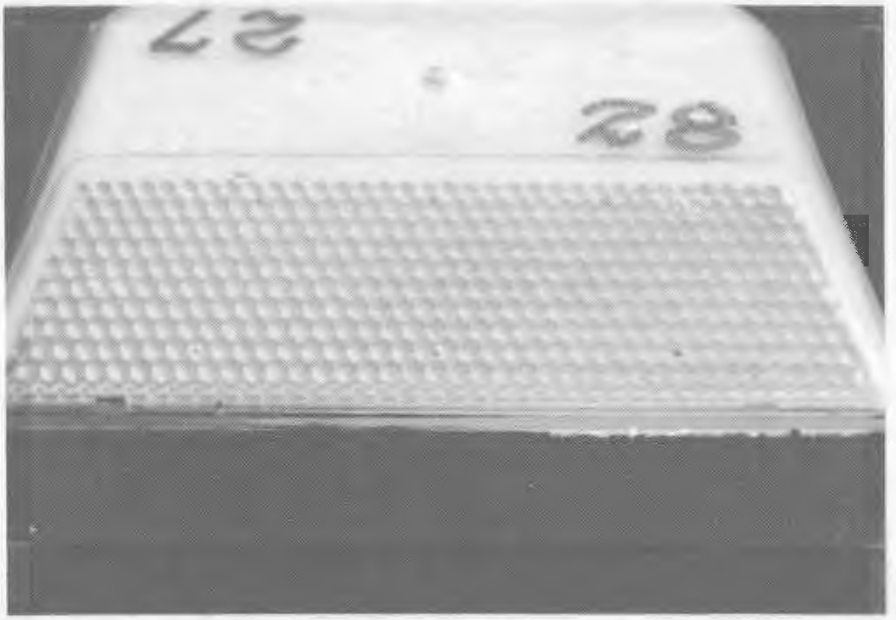


Figure 5-14. Photograph of plastic-faced Model 88 RPM (ID# 28) after 4400 tire impacts.

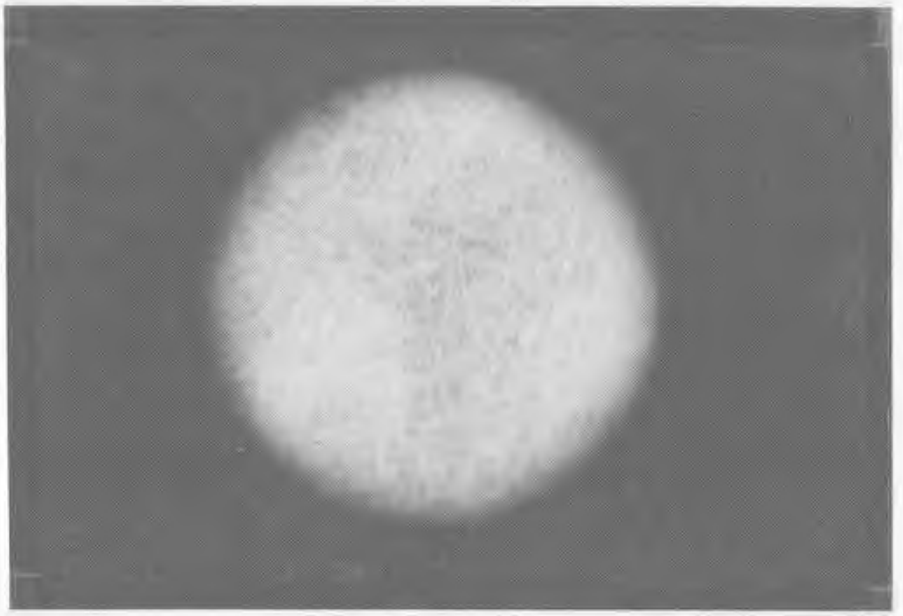


Figure 5-15. Photomicrograph of plastic-faced Model 88 RPM (ID# 28) after 4400 tire impacts.

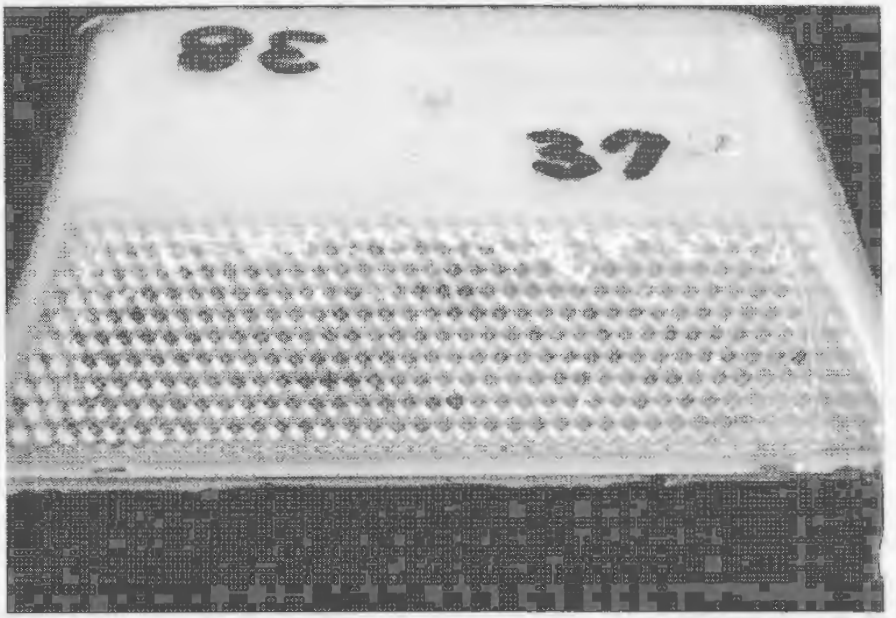


Figure 5-16. Photograph of glass-faced Model 911 RPM (ID# 37) after 4400 tire impacts.

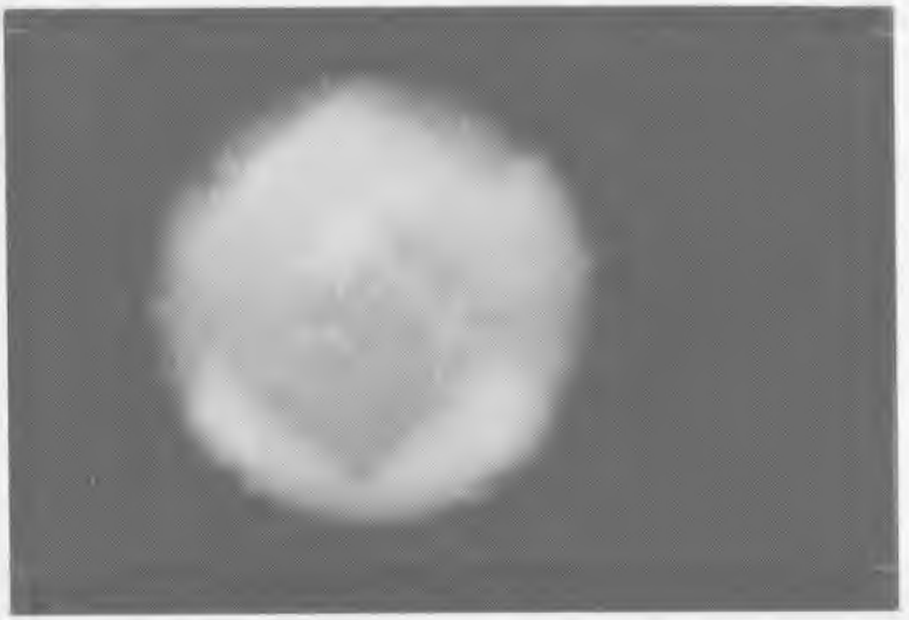


Figure 5-17. Photomicrograph of glass-faced Model 911 RPM (ID# 37) after 4400 tire impacts.

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.

	"Acrylic"		"Epoxy"	
Measurement Period	Mean SI	% Of New	Mean SI	% 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

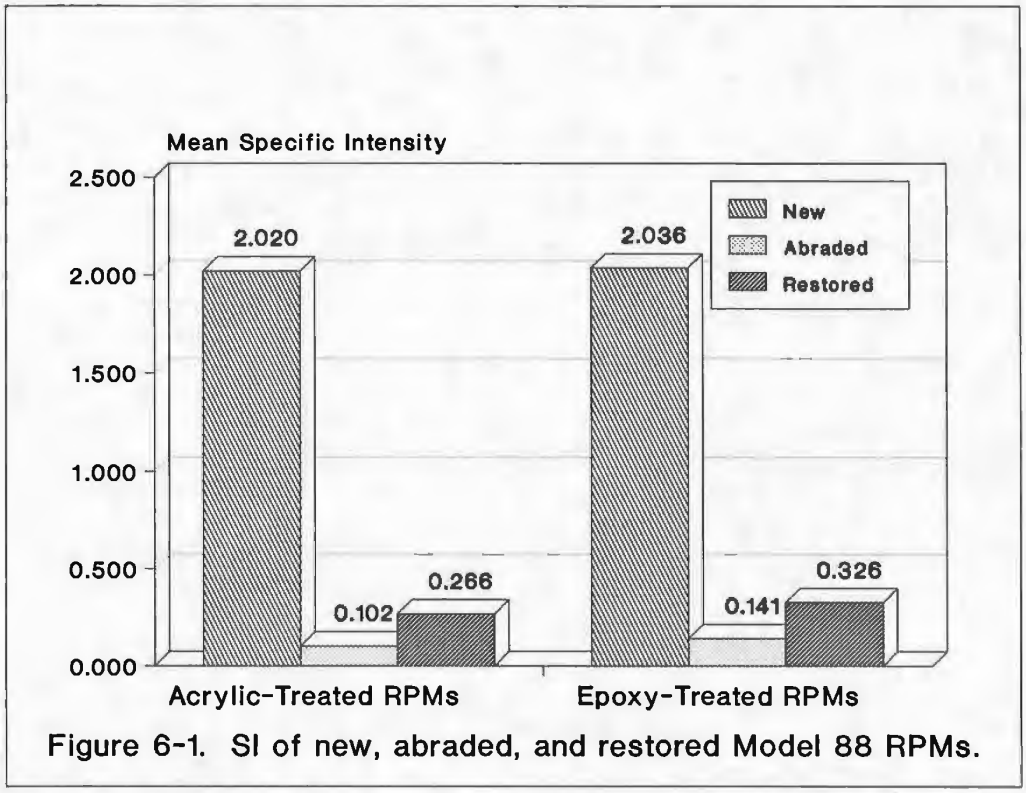


Figure 6-1. SI of new, abraded, and restored Model 88 RPMs.

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.

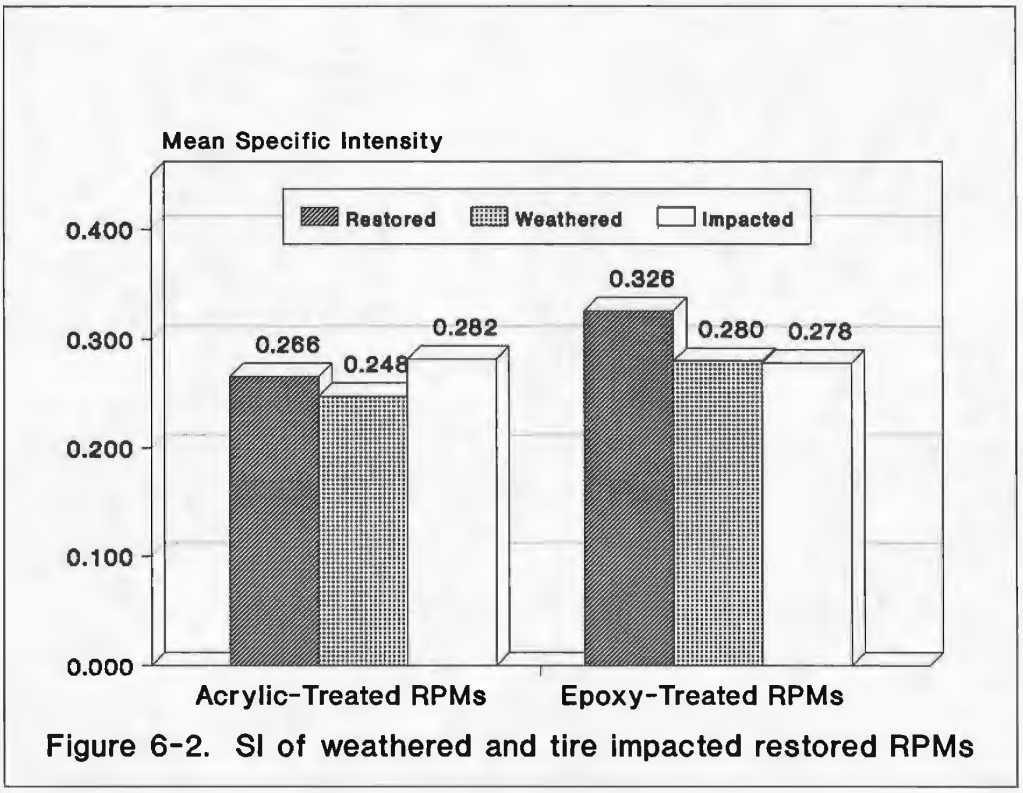


Figure 6-2. SI of weathered and tire impacted restored RPMs

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 retro-reflectivity 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 retro-reflectivity 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

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 retro-reflectivity 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 retro-reflectivity 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

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 retro-reflectivity 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.

9. REFERENCES

American Society for Testing and Materials. (1981) Standard practice for measuring photometric characteristics of retro-reflectors. Designation E 809-81. Philadelphia: Author.

Atlas, D. (1953) Optical extinction by rainfall. Journal of Meteorology, 10, 486-488.

Baerwald, J.E. (Ed.) (1976) Transportation and traffic engineering handbook Institute of Traffic Engineers, Englewood Cliff, NJ: Prentice-Hall, p. 612.

Ivey, D.L., Lehtipuu, E.K. and Button, J.W. (1975) Rainfall and visibility - The view from behind the wheel. Texas Transportation Institute Report 135-3, Texas Highway Department Project 1-10-70-135, 1975.

Kaufman, J.E. (Ed.) (1966) IES lighting handbook, 4th Ed. Illuminating Engineering Society, p. 2-26.

McNees, R.W. and Noel, J.S. (1986) State-of-the-art and objectives of reflective raised pavement markers. Interim report, Study 2-18-82-322, Report No. FHWA/TX-86/10+322-1.

McNees, R.W. and Noel, J.S. (1986) Reflectivity retention of reflective raised pavement markers. Interim report, Study 2-18-82-322, Report No. FHWA/TX-86/11+322-2.

McNees, R.W. and Noel, J.S. (1986) Executive summary, significant results and assorted tests and procedures for reflective raised pavement markers. Final report, Study 2-18-82-322, Report No. FHWA/TX-86/13+322-4F.

Middleton, W.E.K. (1952) Vision through the atmosphere. Toronto: University Press, p. 13-15.

Perel, M., Olson, P.L., Sivak, M. and Medlin, J.W. Jr. (1983) Motor vehicle forward lighting. SAE Technical Paper Series, Paper 830567.

Noel, J.S and McNees, R.W. (1986) Retention of reflective raised pavement markers. Interim report, Study 2-18-82-322, Report No. FHWA/TX-86/12+322-3.

SAS Institute. (1988) SAS user's guide: Statistics, version 6.03, Cary, NC: Author.

Society of Automotive Engineers. (1986) Reflex reflectors - SAE J594f. In 1986 SAE Handbook Vol. 2 Parts and components (pp. 21.94-21.95). Warrendale, PA: Author.

Texas State Department of Highways and Public Transportation (1982) Standard Specifications for Construction of Highways, Streets, and Bridges. Austin, Texas: Author.

Texas State Department of Highways and Public Transportation Materials and Test Division. (1978) Test method for measuring retroreflectivity, Test Method Tex-842-B. Austin: Author.

Tielking, J.T. and Noel, J.S. (1988) On the retention of reflective raised pavement markers. Final report, Research Study 2-10-86-477, Report No. FHWA/TX-87-477-1F.

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

APPENDIX A-1

Books

Optics, illumination, and image sensing for machine vision V : 8-9 November 1990, Boston, Massachusetts

CONFERENCES

Symposium on Advances in Intelligent Systems (1990 : Boston, Mass.)

AVAILABLE AS

Physical

Request a Copy

Save to Lists

Citation

Details

Physical Locations

Verona Shelving Facility **by request only**
TA1632 O685 1991

Publication Details

CREATOR
Donald J. Svetkoff ... [and others], chairs/editors ; sponsored by SPIE--The International Society for Optical Engineering

FORMAT
Books

LANGUAGE
English

CONTRIBUTORS
Svetkoff, Donald J
Society of Photo-Optical Instrumentation Engineers

PUBLICATION
Bellingham, Wash., USA : SPIE, [1991]
©1991

SERIES
Proceedings of SPIE--the International Society for Optical Engineering ; v. 1385

PHYSICAL DETAILS
viii, 293 pages : illustrations ; 28 cm

ISBNS
9780819404527, 0819404527

OCLC
ocm23444399

Notes

"Part of a four-conference program on machine vision system integration held at SPIE's Symposium on Advances in Intelligent Systems, a part of OE/Boston '90, 4-9 November 1990, in Boston, Massachusetts."--P. v.
Includes bibliographical references and index.

Subjects

Computer vision -- Congresses.

Content Types

Congresses

Items Related By Call Number

Shelf Browse

Books **Books** **Books**

Optical interconnects in broadband switching arch...

Optical recording, storage, and retrieval systems...

Optical signal processing

Physical
TA1632 O672 1996

Physical
TA1632 O673 1996

Physical
TA1632 O674 1987

Additional Information

Information from the Web

Library Staff Details

MARC Bibliographic Record

```
LEADER    01617mam a2200337 a 4500
001       9919089253602122
005       20110317122203.0
008       910409t19911991waua     b    10100 eng d
```

```
010          $a   90064018
020          $a0819404527 (pbk.)
035          $a(OCoLC)23444399
035          $9AMU8211UW
035          $a(WU)1908925-uwmadisondb
035          $a(EXLNZ-01UWI_NETWORK)999639084502121
040          $aAZU$beng$cAZU$dGZM
090          $aTA1632$b.O685 1991
245    00    $aOptics, illumination, and image sensing for machine vision V :$b8-9
             November 1990, Boston, Massachusetts /$cDonald J. Svetkoff ... [and
             others], chairs/editors ; sponsored by SPIE--The International Society for
             Optical Engineering.
264    _1    $aBellingham, Wash., USA :$bSPIE,$c[1991]
264    _4    $c©1991
300          $aviii, 293 pages :$billustrations ;$c28 cm.
336          $atext$btxt$2rdacontent
```

```
337          $aunmediated$bn$2rdamedia

338          $avolume$bnc$2rdacarrier

490    1_    $aProceedings of SPIE--the International Society for Optical Engineering
             ;$vv. 1385.

500          $a"Part of a four-conference program on machine vision system integration
             held at SPIE's Symposium on Advances in Intelligent Systems, a part of
             OE/Boston '90, 4-9 November 1990, in Boston, Massachusetts."--P. v.

504          $aIncludes bibliographical references and index.

650    _0    $aComputer vision$vCongresses.

700    1_    $aSvetkoff, Donald J.

710    2_    $aSociety of Photo-Optical Instrumentation Engineers.

711    2_    $aSymposium on Advances in Intelligent Systems$d(1990 :$cBoston, Mass.)

830    _0    $aProceedings of SPIE--the International Society for Optical Engineering
             ;$vv. 1385.

997          $aMARCIVE
```

MMS IDs

Document ID: 999639084502121
Network Electronic IDs:

Network Physical IDs: 999639084502121
mms_mad_ids: 9919089253602122

APPENDIX B-1

Books

Night visibility 1960

AUTHOR / CREATOR

National Research Council (U.S.). Highway Safety Board. Meeting (39th : 1960 : Washington, D.C.)

AVAILABLE AS

Physical

Request a Copy

Save to Lists

Citation

Details

Physical Locations

Holdings for this item have been removed.
Please Ask a Librarian for assistance.

Publication Details

CREATOR
Highway Research Board

FORMAT
Books

LANGUAGE
English

PUBLICATION
Washington : National Academy of Sciences-National Research Council, 1960

SERIES
Bulletin (National Research Council (U.S.). Highway Research Board) ; 255
Publication (National Research Council (U.S.)) ; no. 764

PHYSICAL DETAILS
4 unnumbered pages, 195 pages : illustrations ; 25 cm

OCLC
ocm06589046

Notes

"Presented at the 39th Annual Meeting, January 11-15, 1960."
Includes bibliographical references.

Subjects

Night vision.

Automobile driving at night.

Roads -- Lighting.

Items Related By Call Number

Shelf Browse

Books
Pavement performance concepts: presented at the 3...
National Research Council (U.S.). ...

Physical
TE7 N28 no.250

Books
Asphaltic concrete construction, field and labora...
National Research Council (U.S.). ...

Physical
TE7 N28 no.251

Books
Snow and ice control with chemicals and abrasives...
National Research Council (U.S.

Physical
TE7 N28 no.252

Additional Information

Library Staff Details

MARC Bibliographic Record

LEADER		01353mam a2200325 i 4500
001		9931456913602122
005		20101027111146.0
008		800805s1960 dcua b 000 0 eng d
035		$a(OCoLC)06589046
035		$9ATA2412UW
035		$a(WU)3145691-uwmadisondb
035		$a(EXLNZ-01UWI_NETWORK)999748005302121
040		$aCBT$beng$cCBT$dOCL
090		$aTA1001.5$b.B8 no. 255
110	2_	$aNational Research Council (U.S.).$bHighway Safety Board.$bMeeting$n(39th :$d1960 :$cWashington, D.C.)
245	10	$aNight visibility 1960 /$cHighway Research Board.

```
264    _1    $aWashington :$bNational Academy of Sciences-National Research
             Council,$c1960.

300          $a4 unnumbered pages, 195 pages :$billustrations ;$c25 cm.

336          $atext$btxt$2rdacontent

337          $aunmediated$bn$2rdamedia

338          $avolume$bnc$2rdacarrier

490    1_    $aBulletin / National Research Council, Highway Research Board ;$v255

490    1_    $aPublication / National Research Council ;$vno. 764

500          $a"Presented at the 39th Annual Meeting, January 11-15, 1960."

504          $aIncludes bibliographical references.

650    _0    $aNight vision.

650    _0    $aAutomobile driving at night.

650    _0    $aRoads$xLighting.

830    _0    $aBulletin (National Research Council (U.S.). Highway Research Board)
             ;$v255.

830    _0    $aPublication (National Research Council (U.S.)) ;$vno. 764.
```

997 $aMARCIVE

MMS IDs

Document ID: 999748005302121
Network Electronic IDs:
Network Physical IDs: 999748005302121
mms_mad_ids: 9931456913602122

APPENDIX C-1



Books

Implementation strategies for sign retroreflectivity standards

AUTHOR / CREATOR

Black, K. L. (Kent L.)

AVAILABLE AS

Physical

Request a Copy

Save to Lists

Citation

Details

Physical Locations

This item is also held by UW-Milwaukee

Holdings for this item have been removed.
Please Ask a Librarian for assistance.

Publication Details

CREATOR
K.L. Black, H.W. McGee, and S.F. Hussain

FORMAT
Books

LANGUAGE
English

CONTRIBUTORS
McGee, Hugh W
Hussain, S. F. (Syed F.)
American Association of State Highway and Transportation Officials
National Research Council (U.S.). Transportation Research Board
National Cooperative Highway Research Program

PUBLICATION
Washington, D. C. : Transportation Research Board, National Research Council, 1992

SERIES
Report (National Cooperative Highway Research Program) ; 346

PHYSICAL DETAILS
44 pages : illustrations ; 28 cm

ISBNS
9780309048699, 0309048699

OCLC
ocm25924564

Notes

"Research sponsored by the American Association of State Highway and Transportation Officials in cooperation with the Federal Highway Administration."--t.p.
"April 1992."--t.p.
Includes bibliographical references (page 44).

Items Related By Call Number

Shelf Browse

Books	**Books**	
Bond and insurance coverages for highway construc...	Primer on transportation, productivity, and econo...	
Hancher, Donn E	Lewis, David L. (David Leonard), 1...	
	Online	
Physical	Physical	
TE7 .N25 no.341	TE7 .N25 no.342	

Additional Information

Digital Copies at HathiTrust

Information from the Web

Library Staff Details

MARC Bibliographic Record

```
LEADER    01591mam a22003735a 4500
001       9924366113602122
005       19990604113142.0
008       920602s1992    dcua     b    000 0 eng d
010         $a   92080551
```

020		$a0309048699
035		$a(OCoLC)25924564
035		$9AQA2221UW
035		$a(WU)2436611-uwmadisondb
035		$a(EXLNZ-01UWI_NETWORK)999685544002121
040		$aGZM$beng$cGZM
049		$aGZZK
098	11	aSaN21$aC88$ano.346
100	1_	$aBlack, K. L.$q(Kent L.)
245	10	$aImplementation strategies for sign retroreflectivity standards /$cK.L. Black, H.W. McGee, and S.F. Hussain.
264	_1	$aWashington, D. C. :$bTransportation Research Board, National Research Council,$c1992.
300		$a44 pages :$billustrations ;$c28 cm.
336		$atext$btxt$2rdacontent
337		$aunmediated$bn$2rdamedia
338		$avolume$bnc$2rdacarrier
490	1_	$aReport (National Cooperative Highway Research Program),$x0077-5614 ;$v346
504		$aIncludes bibliographical references (page 44).
500		$a"Research sponsored by the American Association of State Highway and Transportation Officials in

		cooperation with the Federal Highway Administration."--t.p.
500		$a"April 1992."--t.p.
700	1_	$aMcGee, Hugh W.
700	1_	$aHussain, S. F.$q(Syed F.)
710	2_	$aAmerican Association of State Highway and Transportation Officials.
710	2_	$aNational Research Council (U.S.).$bTransportation Research Board.
710	2_	$aNational Cooperative Highway Research Program.
830	_0	$aReport (National Cooperative Highway Research Program) ;$v346.
997		$aMARCIVE

MMS IDs

Document ID: 999685544002121
Network Electronic IDs:
Network Physical IDs: 999685544002121
mms_mad_ids: 9924366113602122
mms_ml_ids: 998344503402124

APPENDIX D-1

```
leader  02247cas a2200529   4500
001     992991883405961
005     20230906181014.0
008     750407c19749999dcu x1m       0   a0eng
010     ##$a   74032372 //r96
012     ##$a3 $b3 $en $i8412 $l1
019     ##$a1589702 $a3587450
022     ##$a0361-1981
030     ##$aTRREDM
035     ##$a(OCoLC)1259379
035     ##$a(Horizon)412491
035     ##$a(MoKL)299188-lhalldb
035     ##$a(lhalldb)299188-lhalldb
035     ##$z(OCoLC)1589702 $z(OCoLC)3587450
040     ##$aDLC $cDAY $dNSD $dDLC $dNSD $dSER $dAIP $dNST $dAIP $dNST $dOCL $dNST $dOCL $dCAS $dDLC $beng
042     ##$ansdp $alc
049     ##$aLHLA
050     00$aTE7 $b.H5
082     ##$a380.5/08
210     0#$aTransp. res. rec.
222     #0$aTransportation research record
245     00$aTransportation research record.
260     ##$aWashington, $bTransportation Research Board, Commission on Sociotechnical Systems, National Research Council, National Academy of Sciences, $c1974-
362     0#$ano. 480-
510     2#$aChemical abstracts, $x0009-2258 $b-1987
510     2#$aCoal abstracts, $x0309-4979
510     2#$aEngineering index annual (1968), $x0360-8557
510     2#$aEngineering index bioengineering abstracts, $x0736-6213
510     2#$aEngineering index energy abstracts, $x0093-8408
510     2#$aEngineering index monthly (1984), $x0742-1974
510     2#$aGeoRef, $x0197-7482
510     2#$aSelected water resources abstracts, $x0037-136X
555     0#$aFor index of TRR publications 1997-2001 see CD-ROM, vol. 1781-1818 (2002).
590     11$aSelected volumes/issues transferred from the Engineering Societies Library, January 1995.
650     #0$aTransportation $zUnited States.
650     #0$aRoads $vCongresses.
710     2#$aNational Research Council (U.S.). $bTransportation Research Board.
780     00$tHighway research record $x0073-2206 $w(OCoLC)1259367 $w(DLC) 68006839
850     ##$aArU $aCaAEU $aCaOTDT $aDLC $aDeU $aFU $aIaAS $aMiD $aMnU $aNIC $aNN $aPPT $aULA $aViU
890     ##$aTransportation research record. (National Research Council. Transportation Research Board). Washington, D.C.
936     ##$aNo. 1508, published in 1995 LIC
945     ##$aTransportation research record. $bTransportation research record.
948     ##$aLTI 02/15/2018
```

APPENDIX E-1

Books; Microforms

An implementation guide for minimum retroreflectivity requirements for traffic signs

AUTHOR / CREATOR

McGee, Hugh W

AVAILABLE AS

Physical

Request a Copy

Save to Lists

Citation

Details

Physical Locations

Memorial Library
Today's hours: 8:30 a.m.–9 p.m.

Memorial Microforms -- ask at Circulation Desk
TD 2.30: 97-052
In-library use only

Items do not circulate. You can view in the library.

Notes

Section A

Microfiche. [Washington, D.C.] : Supt. of Docs., U.S. G.P.O., [1998] 1 microfiche : negative.

Publication Details

FORMAT

Books; Microforms

LANGUAGE

English

CONTRIBUTORS

Paniati, Jeffrey A

Turner-Fairbank Highway Research Center

Bellomo-McGee, Inc

PUBLICATION

McLean, VA : U.S. Dept. of Transportation, Federal Highway Administration, Research and Development, Turner-Fairbank Highway Research Center ; [Springfield, Va. :] : [Available to the public through the National Technical Information Service], [1998]

PHYSICAL DETAILS

v, 51 pages : illustrations ; 28 cm

OCLC

ocm40216985

Notes

Cover title.
Authors: Hugh W. McGee and Jeffrey A. Paniati.
"April 1998."
"Publication no. FHWA-RD-97-052."
Includes bibliographical references (pages 50-51).
Microfiche. [Washington, D.C.] : Supt. of Docs., U.S. G.P.O., [1998] 1 microfiche : negative.

Subjects

Traffic signs and signals -- United States -- Evaluation.

Traffic signs and signals -- United States -- Maintenance and repair -- Management.

Reflectance.

Additional Information

Information from the Web

Library Staff Details

MARC Bibliographic Record

```
LEADER    01882nam a2200409 a 4500
   001    9950382313602122
   005    20180323033648.0
   007    he bmb024bbca
   008    981102s1998    dcua    bbt  f000 0 eng d
   035          $a(OCoLC)ocm40216985
   035          $a(WU)5038231-uwmadisondb
   035          $a(EXLNZ-01UWI_NETWORK)999896707502121
   040          $aWU$beng$cWU$dGPO$dDLC$dMvI$dMGPO
   049          $aGPO
   074          $a982-G-11 (MF)
   086    0_    $aTD 2.30:97-052
```

088 $aPublication no. FHWA-RD-97-052

100 1_ $aMcGee, Hugh W.

245 13 $aAn implementation guide for minimum retroreflectivity requirements for traffic signs.

264 _1 $aMcLean, VA :$bU.S. Dept. of Transportation, Federal Highway Administration, Research and Development, Turner-Fairbank Highway Research Center ;$a[Springfield, Va. :] :$b[Available to the public through the National Technical Information Service],$c[1998]

300 $av, 51 pages :$billustrations ;$c28 cm

336 $atext$btxt$2rdacontent

337 $amicroform$bh$2rdamedia

338 $amicrofiche$bhe$2rdacarrier

500 $aCover title.

500 $aAuthors: Hugh W. McGee and Jeffrey A. Paniati.

536 $aPerformed by Bellomo-McGee, Inc. (BMI) and sponsored by the Federal Highway Administration Office of Safety and Traffic Operations R&D under contract no.$bDTFH61-93-C-00131.

500 $a"April 1998."

```
504          $aIncludes bibliographical references (pages 50-51).

500          $a"Publication no. FHWA-RD-97-052."

533          $aMicrofiche.$b[Washington, D.C.] :$cSupt. of Docs., U.S.
             G.P.O.,$d[1998]$e1 microfiche : negative.

650    _0    $aTraffic signs and signals$zUnited States$xEvaluation.

650    _0    $aTraffic signs and signals$zUnited States$xMaintenance and
             repair$xManagement.

650    _0    $aReflectance.

700    1_    $aPaniati, Jeffrey A.

710    2_    $aTurner-Fairbank Highway Research Center.

710    2_    $aBellomo-McGee, Inc.

997          $aMARCIVE
```

MMS IDs

Document ID: 999896707502121
Network Electronic IDs:
Network Physical IDs: 999896707502121
mms_mad_ids: 9950382313602122

APPENDIX F-1

Raised pavement marker reflectivity /

Corporate Authors:	Texas. State Department of Highways and Public Transportation, Texas Transportation Institute
Other Authors:	Pezoldt, Val
Format:	Government Document, Book
Language:	English
Published:	College Station, Tex. : Springfield, Va. : Texas Transportation Institute, Texas A&M University System ; Available through National Technical Information Service, [1990]
Series:	Research report (Austin, Tex.) ; 1151-1F.
Subjects:	Road markings. Reflectors (Safety devices) Roads > Safety measures.

Holdings Description Similar Items Staff View

MARC

LEADER	00000cam a2200000 a 4500
001	in00001038161

005	20150928150947.0		
008	910809d19901100txu	tb s000 0 eng d	
035			**|a** (OCoLC)24207129
035			**|9** AFH0190AM
040			**|a** IKM **|c** IKM **|d** TXA **|d** UtOrBLW
049			**|a** TXAM
086			**|a** H1333.7 R311 no. 1151-1F **|2** txdocs
090			**|a** HE203 **|b** .T43 no.1151-1
245	0	0	**|a** Raised pavement marker reflectivity / **|c** by V.J. Pezoldt [and others].
264		1	**|a** College Station, Tex. : **|b** Texas Transportation Institute, Texas A&M University System ; **|a** Springfield, Va. : **|b** Available through National Technical Information Service, **|c** [1990]
300			**|a** xii, 107 pages : **|b** illustrations ; **|c** 28 cm.