# MINIMAL LUMINANCE REQUIREMENT FOR OFFICIAL HIGHWAY SIGNS

Research, Development, and Technology

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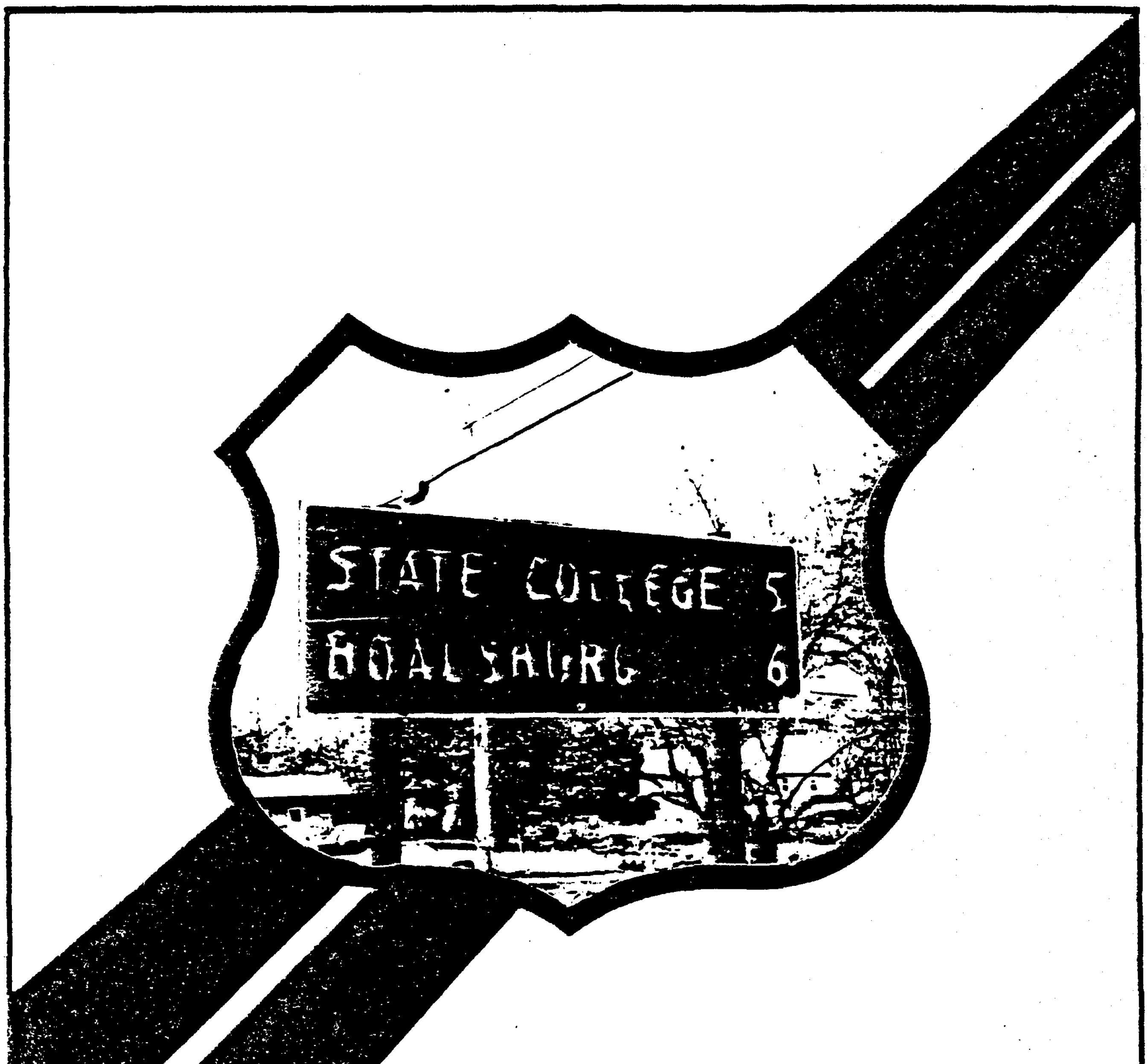

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16. Abstract

The objectives of the study were to establish minimal levels of sign luminance for various signing applications and conditions, and to develop a structure for determining sign maintenance priorities. The objectives were addressed via development of a system for maintenance of sign reflectivity with luminance standards embedded in the system.

This report provides an overview of the problems of implementing luminance standards. It presents a discussion of the major factors essential to a computer-based system to implement reflectivity standards. It describes a decision-support system developed for use in managing and maintaining sign inventories. It also describes an empirical study designed to evaluate several aspects of this system. The empirical study showed that use of the system for making decisions about sign replacement based on specific intensity per unit area (SIA) produces results comparable to results produced by experts making sign replacement decisions. A final section states that the system could provide a cost-effective tool for use by State or local agencies, but would depend on information that establishes a relationship between sign material age and location, and sign brightness. Such data are not yet available in the literature. The report also includes two appendices covering analytical determination of minimum brightness standards for sign legibility, and luminance of retroreflective materials and their deterioration.

Volume 2, an executive summary, presents a condensed version of this report of research.

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DECISION SUPPORT AND REPLACEMENT STANDARDS IN THE MAINTENANCE OF TRAFFIC SIGN VISIBILITY

Key decisions facing every administrator with responsibility for maintaining reflectorized signs on streets and highways relate to what signs to install, where to install them, and when to replace them. The development of automated sign inventories and road logs over the next few years will offer an opportunity for the introduction of innovative software to provide more efficient and objective solutions to the problems of sign maintenance management. Administrators, engineers, and shop foremen will be able to obtain simple and convenient support for decision making and management of sign maintenance activities using a microcomputer. The software will offer the potential for improvements in public safety by implementing sign visibility standards in a practical and cost-effective manner.

The existing Federal standards for luminance of retroreflective materials for traffic signs are acceptance standards but provide no differentiation based upon driver needs. The Manual on Uniform Traffic Control Devices (MUTCD) 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.[1] There are no minimum initial or replacement requirements for retroreflective signs. New signs are installed with varying reflectivity depending on the material chosen. Replacement is left to practices which vary between States and levels of government within States.

The need for standards is suggested by reports of increasing costs arising from tort liability cases. In addition to the absence of signs, inadequate reflectivity is often cited as a basis of award. The Federal Register has cited the overrepresentation of nighttime accidents as an additional reason to implement standards to maintain sign reflectivity at necessary levels.[2] The objectives of the research reported here were to:

- Establish minimal levels of sign luminance for various signing applications and conditions.
- Develop an overall structure to identify maintenance priorities and schedules.

The purpose of this research, therefore, was to develop a system for maintenance of sign reflectivity with luminance standards embedded in the system. Conducting new research with regard to driver requirements for sign luminance was not within the scope of work. The system developed was therefore limited to the validity of luminance requirements which could be generated from the research already completed and available in the literature.

The report is divided into four main sections. In the first section we will attempt to provide an overview of the problem of implementing luminance standards and of related issues. The second section presents a discussion of the major factors essential to a computer-based system to implement reflectivity standards. These general factors include the choice of a measurement scale, method of measurement and relevant subsets for differential standards including situational factors and sign classification. the third section describes a decision support system developed as part of this research. In recognition of the fact that many characteristics cannot be specified without more research and evaluation, the system was built to be flexible with respect to the alternatives discussed in this section. The second and third sections provide a broad discussion of issues to be considered and a system design adaptable to different operating environments and replacement strategies. The fourth section describes an evaluation of the system and discusses its value with respect to several alternative criteria. This evaluation considered only a subset of the ways the system might be implemented.

## 1. Alternative Approaches to the Specification of Luminance Standards

Research has shown that drivers require a minimum amount of luminance for both legibility and detection. The specification of minimal luminance requirements for traffic signs to satisfy these needs has been addressed by a number of researchers with varying degrees of success.

With respect to nighttime legibility, at least three different approaches can be taken toward specification of minimum brightness standards. Historically, a sign was considered sufficiently bright if it provided approaching drivers with a minimum of 50 feet of legibility per inch (5.9 m/cm) of letter height (Smyth, 1947).[3] However, the selection of 50 ft/in as a minimum legibility distance was quite arbitrary. It is conceivable, for example, that on a low-speed road, a sign with 40-ft/in (4.8 m/cm) legibility or less still provides drivers with enough time to safely respond to that sign's message. Conversely, on a high-speed facility, a particular sign may have to provide 60-ft/in (7.2 m/cm) legibility or more to enable a safe and comfortable response.

A second approach to defining minimum brightness standards is to consider a sign's level of brightness satisfactory if it provides a legibility distance that is greater than or equal to 85 percent of the maximum obtainable nighttime legibility distance (Elstad et al., 1962).[4] Like the first approach, this criterion is also too arbitrary to be useful: 85 percent of maximum legibility distance may or may not be adequate for a given situation. The actual legibility distance required by a driver depends on such factors as the speed limit of the roadway and the time required by the driver to read a sign, respond to its message, and execute any required maneuver. It should be noted, too, that symbol signs do not have to be "read" (i.e., legible on the smaller details of the symbol). Legibility is really a special case of recognition that applies to alpha-numeric legends on signs, legends that must be read to be understood. Symbol signs have to be visible enough so that their symbol can be recognized and a meaning associated with it.

A third approach to establishing minimum brightness standards, then, is to identify the level of brightness needed of a given sign on the basis of the recognition or legibility distance requirement of that sign. In general, a sign must be bright enough to provide a recognition or legibility distance sufficient for drivers to process and respond to the sign's message in a particular driving situation (McGee and Knapp, 1978).[5] The recognition or legibility distance required of a sign can be quantified by using the decision sight distance (DSD) model (McGee et al., 1978) to compute the distance needed by a driver to: detect the sign, recognize or read its message, decide on an appropriate course of action, initiate a control response, and complete the required maneuver.[6] (Note that the five components of the model do not apply to all signs: a NO LEFT TURN sign, for example, does not require a driver control response or vehicle maneuver.) A sign's minimum recognition or legibility distance requirement, then, corresponds to the distance at which the sign must be recognized or read to afford drivers time to respond appropriately and safely. By extension, a sign's minimum brightness requirement is the level of brightness it must have to provide a recognition or legibility distance that exceeds the required distance.

Since the last approach is the only one of the three that does not incorporate an arbitrary legibility distance requirement for alpha-numeric signs, the DSD model should be applied as the basis for deriving minimum brightness standards. Specifically, after the legibility distance requirement--expressed in feet--has been computed via the DSD model for a given sign in a particular situation, this distance can be divided by the sign's letter height--expressed in inches. The resulting quotient represents the required legibility distance--expressed in feet per inch--for the sign under consideration. In order to determine the minimum level of brightness required of that sign to meet the legibility distance requirement, a table that describes legibility performance as a function of brightness is needed. An appropriate expansion of this approach would be to extend the brightness requirements to insure adequate conspicuity in visually complex environments. The model implemented in this research used a fixed time for detection. (Only one study [Mace et al., 1985] provides any data which would be useful in determining the time required for adequate conspicuity.[7] As additional research is completed, the model should be modified to vary the detection component of DSD with levels of visual complexity.)

## 2. Problems Related to the Implementation of Luminance Standards

Earlier research which has focused on luminance requirements for legibility and standards for replacement has been expressed in terms of specific luminance, i.e., reflectivity (Olson and Bernstein, 1977; Sivak and Olson, 1985).[8,9] Mace et al. (1985) made recommendations with regard to the conspicuity of yellow diamond warning signs with replacement standards expressed in units of reflectivity and brightness.[7] Although research has been conducted which is relevant to the question of standards, standards have not yet been implemented.

There are two reasons why there are no standards which reflect fundamental driver needs. First, there is an absence of conclusive performance data supporting minimal luminance standards. Second, there is no practical and reliable way of measuring luminance in the field, and therefore one cannot easily determine if the requirements are met. Even where data are available and criteria agreed upon, a number of critical problems make the development of standards an extremely complex task. One problem already mentioned is that luminance is required for two distinct and not necessarily compatible purposes: recognition, or legibility, and conspicuity. A second equally fundamental problem which is easily overlooked is that the population of signs is not uniform in purpose or function. Signs are created in different designs to serve different needs, and these differences create substantial differences in the luminance required for them to function properly at night.

Signs vary in the redundancy of information contained which affects the need for recognition or legibility. Luminance required will therefore depend on how a sign is designed. The STOP sign shape and color must be discriminated, but its legend need not be legible, for the sign to communicate its message. The speed limit sign numbers must be legible, but not the smaller letters in the words SPEED or LIMIT. Signs also vary with respect to drivers' expectation and motivation to find them. This variation affects the need for conspicuity. Luminance required will therefore depend on the function of the sign, e.g., to warn drivers of an unexpected hazard or provide directional information to those searching for it.

The importance of motivation and expectancy is seen by considering three types of conspicuity problems which drivers encounter at night. Detecting unexpected hazards which have a low frequency of occurrence is the first problem. A second problem is the detection of things, such as lane delineation and guide signs, which are expected and actively searched for. The third conspicuity problem concerns the detection of unexpected traffic signs such as regulatory and warning signs. These, and other conspicuity problems, can all be represented in three dimensions defined by background complexity, expectancy, and driver motivation. For example, some situations of STOP sign placement have good conspicuity because expectancy is high due to the fact that the driver has encountered STOP signs in the same position at regular intervals. In other situations where expectancy is low, conspicuity may be raised by increased motivation created by an advanced warning. These dimensions are reflected in our definition of conspicuity, which is as follows:

> Conspicuity, like visibility and recognizability, is not an observable characteristic of an object, but a construct which relates measures of perceptual performance with measures of background, motivation, and uncertainty.

Implicit in this definition is that conspicuity, in a functional sense, is not dependent solely upon sign brightness. Factors such as driver uncertainty and expectancy, alertness, etc., may be equally as important as brightness in determining the minimal requirement for sign detection. A STOP sign following a STOP AHEAD sign will be more conspicuous because the driver's uncertainty about its presence is reduced. Directional signs are more easily detected by drivers looking for them, and the increased motivation which occurs when someone is lost makes all signs more conspicuous. It is likely that the difference in motivation and uncertainty provided to experimental subjects is often the basis for inconsistencies in experimental results. We therefore suggest that it may be necessary to include a level of motivation and uncertainty in the concept of a design driver when specifying luminance requirements for a sign. A proposal to classify signs on the basis of design levels of motivation and uncertainty for the purpose of developing differential luminance standards is provided in the second section of this report.

The problem of specifying luminance standards for traffic signs is complex and multidimensional. Driver requirements of different signs change across situations. Very little data exist on the luminance required for recognition of symbol signs or luminance required for conspicuity. Even where a large body of literature exists, such as luminance required for legibility of alphabetic signs, unequivocal results are not obtained and the effects of a number of critical variables have not been adequately documented.[1] Even if the brightness requirements could be specified, a question

[1]Appendix A reviews literature concerned with luminance required or legibility.

would still exist whether to express the standards in photometric terms (candelas per square foot) or in terms of the reflectivity of the sheeting (specific intensity per unit area [SIA]).[2] The difficulties in choosing between these alternative measures are discussed in second section.

3. <u>Issues Related to the Design of a System for Implementation of Standards</u>

To be effective, any system for implementing luminance standards must be simple, reliable, and affordable. Finding agreement on what is reliable and affordable will not be easy. Consider one of the simplest systems, such as keeping a record of sign installation dates and material type, and replacing all signs of type II sheeting (engineering grade) when 5 years old and type III (high intensity) sheeting when 12 years old. The labor cost of this type of procedure is low because it does not require field evaluation. Total implementation cost of such a procedure, however, may be very high. Certainly a high false negative rate (a sign replaced when it is still adequate) would be expected, making the sign replacement budget greater than necessary. One would expect the false positive rate to be low, except that there are signs which are essentially new but nonreflective because of errors in the fabrication of the sign. Also, some signs simply need to be moved a few feet, reoriented, or washed to have their performance dramatically improved.

In order to minimize false negatives, one must sacrifice simplicity. The extreme case which would minimize false negatives would be a system which supports a customized performance requirement; i.e., the minimum luminance for any sign in a given location must consider the specific type of sign, what it must do, how it is designed, and the situational factors regarding where it is placed (e.g., approach speed, visual complexity, etc.). How complex such a system would be depends in part on how much automation is available. Given computer access to the necessary information, software could be written to provide a list of signs and their minimum recognition, legibility,

[2]One footLambert (fL) = 0.318 candelas per square foot (cd/ft$^2$) = 3.43 candelas per square meter (cd/m$^2$). Specific intensity per unit area is an expression of candelas per footcandle per square foot (cd/fc/ft$^2$). (1 cd/ft$^2$ = 10.76 cd/m$^2$; 1 fc = 1 lumen/ft$^2$ = 10.76 lumen/m$^2$.)

or conspicuity requirements. Both daytime and nighttime inspection should be performed on a rotating basis so that signs that do not require replacement may be handled in the most economical and practical way.

Between the simplest and most complex procedures lie a number of alternatives which have to be explored before a system can be developed. Factors which have to be considered in choosing a system include the accessibility of different types of information and how standards are expressed in terms of legibility, recognition, luminance, or reflectivity. To assist in this determination we conducted phone interviews with traffic engineers from State agencies to determine current practice and to help estimate what might be feasible.

Many of the agencies contacted claim to conduct regularly scheduled nighttime inspections, generally on an annual basis. For some States, budgetary constraints and personal biases create differences within the State as to the amount and regularity of nighttime inspections. Traffic engineers differ on their estimate of the value associated with such inspections. The typical procedure has an inspector drive past a sign to evaluate the level of brightness and estimate its adequacy. This is the procedure followed in the field evaluation detailed in the fourth section of this report. The criterion of "too dark," if defined at all, is based upon some aspect of legibility or recognition. None of the States contacted reported the use of any photometric device such as a reflectometer or telephotometer.

The interviews revealed a general interest in the broad area of sign maintenance management, but there does not seem to be any emphasis on problems of reflectivity. Cracking is seen by some to affect daytime legibility or recognition more than reflectivity. Several people report using daytime inspection to estimate nighttime performance. This, however, is justified on economic grounds rather than data. Most reports of required sign maintenance are generated by policy reports or casual observation of highway personnel. At least one State follows a practice of replacing signs that are more than 5 years old. The arguments for such a simplistic system are that the cost of false negatives is offset by cost savings for inspection and added safety from fewer false positives.

Few studies have been conducted on the effects of aging on sign performance. Some States report their belief that there are too many uncontrollable factors to allow predicting deterioration based upon age alone. (The variables which effect aging and the reasons why valid estimates of deterioration cannot be made are discussed in appendix B.) As will be seen, there are many things which happen to signs which affect visibility but have nothing to do with age. Such problems may even occur before a sign is installed. Another problem is that signs of apparently similar sheeting in fact differ in reflectance when new. A system which bases decisions about replacement or the need for inspection on age alone would not be adequate.

Computerized sign inventories are under development in several States; however, there is not yet any clear indication of how they will be used. Everyone agrees they are a good idea, but starting any kind of formal system is difficult. Models which have been developed focus on materials needed (e.g., feet of U-channel) and their cost. The data-based inventories that do exist serve to provide some suggestions about what types of information might be available to a decision support sign management system. The following items appear in all inventories:

- Location.
- MUTCD code.
- Placement (e.g., left, right, overhead).
- Size.

Other items of information which are sometimes included in a computer-based sign inventory are:

- Type of sheeting.
- Type of backing.
- Type of support.
- Condition of sign.
- Condition of post.
- Date of installation.

In developing the system described in the third section of this report, recognition was given to the reality of what information was likely to be available. A more accurate system might be devised, but the costs in system overhead (with respect to data acquisition and storage) would make the system difficult to use and impractical. Even with these tradeoffs, the type of system proposed has the potential to reduce the error rate inherent in the various manual and casual systems currently used. The system design is flexible so that improvements can be easily made to utilize information available but not used now, and to integrate the results of new research data which might make the decisions of the system more valid.

## KEY DIMENSIONS FOR SIGN REPLACEMENT SYSTEM

Before looking at the system or how it was evaluated, it is important to have an understanding of the applicable dimensions and the choices available in its design. This section presents a discussion of the major factors essential to a computer-based system to implement reflectivity standards, including the choice of a measurement scale, method of measurement, and relevant subsets for differential standards.

### 1. Measures for the Use of Sign Replacement Standards

#### a. The Concept of Supply and Demand

The implementation of a standard for replacement of traffic signs requires an assessment of how much visibility is required (demand) and how much visibility is available (supply). Whatever measure of visibility is used, supply and demand must be assessed along a common scale so that relevant comparisons may be made. In general, the alternatives include measures of driver performance (e.g., legibility, recognition, or detection distance) and measures of sign performance (e.g., specific luminance and available luminance). If legibility, recognition, or detection distance were chosen as the measure of supply, driver information processing requirements would be stated in time and converted to distances based upon assumed speed to arrive at a comparable measure of demand. If photometric luminance were the measure of sign performance, the required luminance for legibility or recognition would be specified for different letter heights, symbols, etc., and the required luminance for conspicuity would be differentiated for different background complexities. Once a measure were chosen, replacement guidelines could be specified.

#### b. Measurement Techniques

There are three general approaches to the measurement of sign performance at night. First, a retroreflectometer may be used in the field to measure current specific luminance. Second, luminance may be measured in the field with a photometer to determine how bright a sign will appear to a driver at a specific distance and lane position. A third method is to use a driver performance measure such as sign legibility or recognition distance.

With regard to the problem of measuring sign performance, consideration must be given to cost, accuracy, reliability, and ease of use. A number of problems exist using a photometer in the field. The equipment is expensive, fragile, sensitive to a number of sources of error, and not easy to use. The retroreflectometer is also relatively expensive and fragile, but it is easier to use than the photometer and is not sensitive to as many sources of error. In an effort to find a simpler method to approximate the measurements of these two instruments, two alternatives which could be used to provide subjective estimates of the same scales were evaluated in a controlled field study. A method using degraded test patches was tested for the purpose of estimating reflectivity, and a method using an electroluminescent panel as a standard was tested for the purpose of estimating photometric brightness. Legibility as a driver performance measure was also included in the study.

The driver performance measure was included mostly for the purpose of comparison and not as a viable method for sign measurement. Like the test patch and electroluminescent panel techniques, the measurement of legibility is subjective. Unlike these other subjective measures, which use comparison stimuli as a control, the legibility measure has no practical way of eliminating differences in the visual performance of different observers. Furthermore, the response of legible versus not legible has a greater amount of error due to semantic interpretation than the "greater than" or "equal to" comparison of the other techniques.

c. Field Evaluation of Alternative Measurement Techniques

A controlled field test was conducted in a shopping center parking lot with a straight uninterrupted run of 1,000 ft (305 m). This facility approximated actual road conditions having a macadam surface and luminaires of standard design and brightness. Testing was done during the late night and early morning hours when the stores were closed and the lot was empty.

This time period allowed the manipulation of stimuli and afforded control of the experimental environment without the attendant noise and problems of "on road" studies. Two levels of ambient illumination, bright and dark, were achieved by manipulation of the luminaires, and two levels of sign surround luminance were provided by a portable, internally illuminated panel placed behind the stimulus. The stimulus was mounted on a standard, commercially available sign post.

A set of 21 test signs ranging in specific intensity per unit area (SIA) from 5 to 216 was selected from a large candidate set comprised of standard field devices removed from service by local highway agencies. All of the candidate signs were measured with a retroreflectometer, and the final selection of test signs was made based on color, material, physical condition, and brightness. Signs of good condition were selected to represent a range of brightness levels (or photometric degradation) for each of five colors (yellow, white, red, orange, and green).

Three methods of measuring sign peformance were formally evaluated, and two other methods were incidentally associated with the study. Following are brief descriptions of the five methods employed.

(1) Comparison Standard. This technique required the subjects to make a judgment about how bright a sign was when compared to four patches of the same type and color of reflective sheeting, each with a different brightness level. A strip of four patches was attached by the experimenter to the center of the sign. Subjects then went to a point 60 ft (18 m) from the sign and illuminated the sign with a flashlight held next to their eyes. A judgment was then made as to the closest match between the sign and patches.

(2) Electroluminescent Panel. The use of an electroluminescent (EL) panel as a comparison standard was evaluated as a novel technique for obtaining a surrogate of photometric luminance. The EL panel was color matched to the Federal specifications for yellow engineering grade sheeting, and was adjustable for six levels of brightness. Two procedures were tested: sign mounted and vehicle mounted. For the sign mounted procedure, the EL panel

was affixed to the sign face similar to the test patch comparison technique. For the vehicle mounted technique, the EL panel was affixed to the center front of the vehicle, just in front of and above the hood. All trials were from a stationary vehicle at a distance of 300 ft (91 m) from the sign. Both high and low ambient lighting conditions were represented; however, only the low surround luminance condition was represented.

Two subjects were seated in the vehicle, one passenger and one driver, and both were required to identify the closest brightness match between the EL panel settings and a sign that was illuminated by the headlamp low beams. The EL panel was stepped through, both ascending and descending, the six available brightness settings and a judgment was then made and recorded.

(3) Legibility. The legibility task required a subject to ride as a passenger in a vehicle that was moving towards a sign, and to identify the point at which the sign was legible. A 2,500-ft (762 m) loop within the parking lot, with a 1,000-ft (305 m) straight approach to the sign was used for testing. The vehicle was driven towards the sign at a slow, uniform speed (approximately 25 mi/h [40 km/h]), and the subject activated a digital measuring instrument (DMI) at the point at which the sign was legible; the driver then continued to the sign and stopped, whereupon the distance reading was recorded on a worksheet.

(4) Incidental Methods. Incidental to the conduct of the controlled field study, as well as to virtually all other phases of the project, was a need for baseline and ground truth measures of luminance and retroreflectivity. These measures were acquired by the experimenters with a Spectra-Pritchard photometer and a Retro-Tech Retroreflectometer. Much hands-on experience was gained with these devices as lab and field instruments.

To evaluate the data collected using the EL panel and the test patch method, the subjective data were converted to estimates of photometric luminance and reflectivity (SIA) respectively. The subjective estimates were then correlated with the ground truth data obtained using the photometer and reflectometer. In both cases correlations over .90 were obtained, with the correlation for test patch estimates with SIA at .99. The correlation of .90 obtained with the EL data represents photometric estimates made with the EL panel mounted on the sign. When the panel was mounted on the vehicle, the correlation dropped to .30. Both sign mounted methods performed equally well under all ambient and surround illumination conditions represented.

While high correlations were obtained using either the EL panel on the sign or the test patch method, the latter was higher (100 percent versus 80 percent variance accounted for) and would be easier to use. The slope of 1.4 for photometric estimates using the EL panel indicates that a regression formula is necessary to make predictions concerning photometric brightness. The test patch data had a slope close to 1, indicating that estimates of reflectivity can be made without conversion by a regression equation. This is eminently clear from an inspection of figures 1 and 2. Figure 1 contains a line graph of estimates using the test patches and ground truth SIA obtained using a reflectometer. Figure 2 contains a line graph comparing estimates using the EL panel with ground truth luminance measurements obtained using a photometer.

The legibility data were analyzed by converting legibility distance to distance per inch of letter height. The correlation of distance per inch with SIA was only .46 to .56, depending on the ambient and surround conditions. As expected, this procedure did not reflect the differential requirements of the different conditions: ambient illumination increasing legibility distance and surround luminance decreasing legibility distance. The low correlation of distance per inch and SIA suggests that there is considerable error in this measure. The source of the error could be the procedure for recording distance responses, vision anomalies, or variation in subjective interpretation or confidence in making a decision that legibility occurred. We suspect all three enter into the unaccounted variance using this performance measure, and therefore do not recommend its use.

The choice of a measure must consider a variety of factors. To aid in a decision, figure 3 presents information comparing the five measurement methods associated with the field study. The methods are compared across a number of critical dimensions.

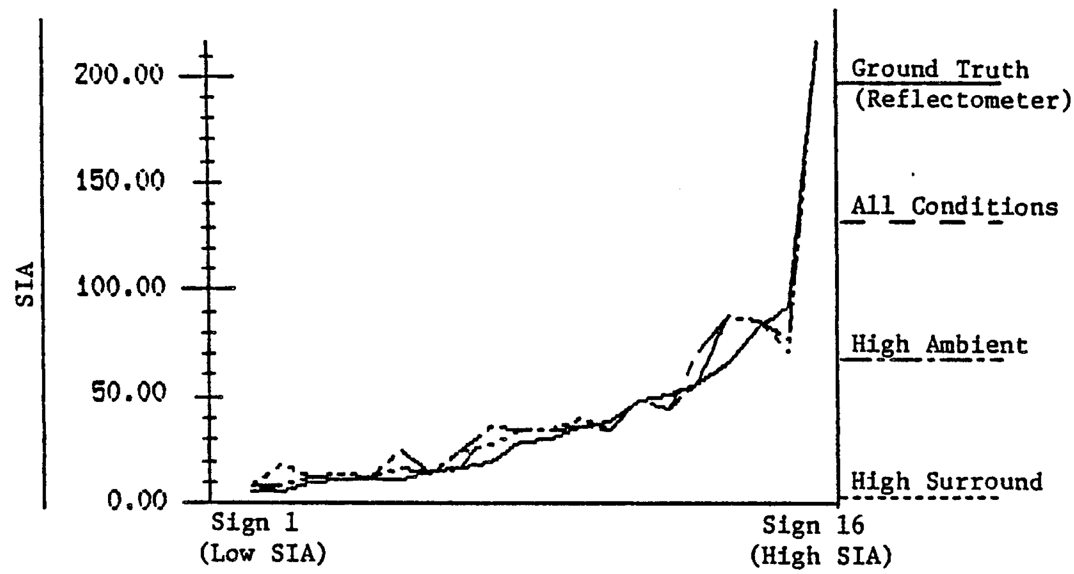



Figure 1. Comparison of estimates of reflectivity (SIA) from degraded test patches and reflectometer measurements for 16 signs.

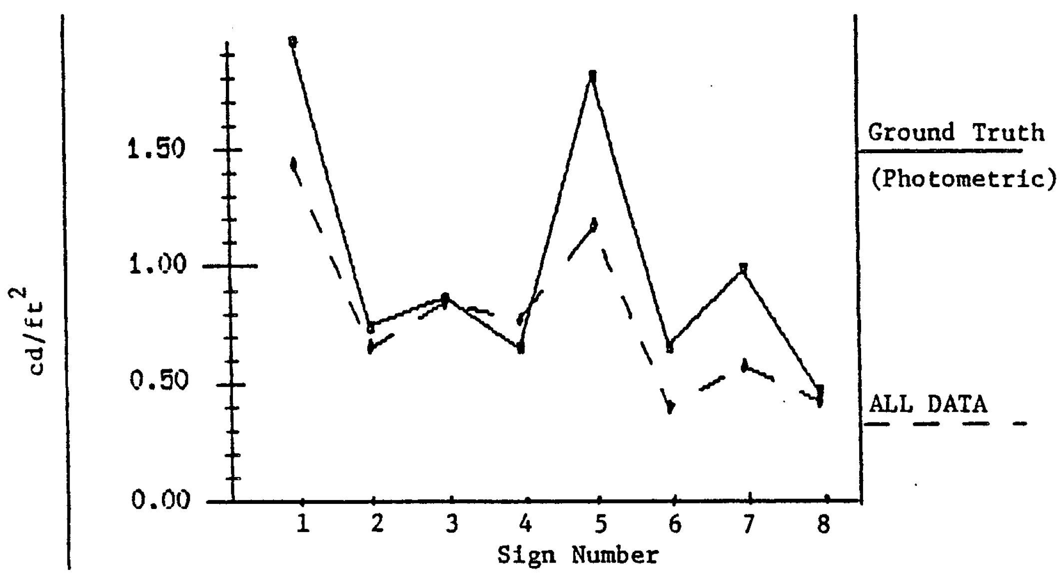



Figure 2. Comparison of estimates of luminance (cd/ft$^2$) from electroluminescent panel and photometric measurement for eight signs.

Note: 1 fL = 0.318 cd/ft$^2$ = 3.43 cd/m$^2$.

With regard to required performance, consideration must be given to the validity of requirements expressed using the measure. This is difficult to accomplish. Which is likely to be more valid, a statement saying drivers require 50 feet of legibility distance per inch (5.9 m/cm) of letter height, or an estimate of required legibility distance based upon unreliable assumptions and questionable generalizations? The truth is that none of the measures lends itself to the expression of valid requirements. Driver requirements expressed using any of these measures will have so much error that, to maintain safety, it is essential that a high false negative rate be accepted (i.e., adequate signs will be replaced) in order to minimize the false positivies (i.e., signs left in place which should be replaced). This does not mean that none of the measures should be used. False negatives and false positives will occur whether or not a formal system is used, and by developing a system to implement standards the error can be put under management's control.

d. Predicting One Performance Measure from Another

An alternative to measurement is prediction. A general paradigm of the relevant reasoning is shown in figure 4. The original material specification (type and SIA) may be used to predict the current SIA. The current SIA may be used to predict current luminance, and current luminance may be used to predict legibility, or recognition, and detection distances. An empirical measure of SIA can be used in place of the predicted measure to increase the accuracy of the predicted photometric luminance. Likewise, an empirical measure of available luminance may be substituted to increase the accuracy of predicted legibility, or recognition, and detection distances. The effect on prediction of using alternative empirical measurements for input to the model is summarized in figure 5.

Instead of recording empirical estimates of legibility or sign detection distance, these distances can be estimated from a measure of photometric luminance (either itself predicted or empirically obtained) using the most relevant data from the literature. Our own summary of the literature relevant to luminance requirements for legibility or alphabetic signs is provided

| | Comparison Standard | Legibility | Electrolum-inescent Panel | Retro-Reflectometer (Model 910F) | Photometer (Model 1980) |
|---|---|---|---|---|---|
| Operator(s) | | | | | |
| Training | Moderate | Moderate | Moderate | Minimal | Extensive |
| Manpower | 1 or 2 | 2 | 2 | 1 | 1 or 2 |
| Vision Testing | Required | Required | Required | N/A | N/A |
| Use | | | | | |
| Time of Day | Night Only | Night Only | Night Only | Day Or Night | Night Only |
| Scale | Subjective | Subjective | Subjective | Objective | Objective |
| Accuracy | Excellent | Poor | Good | Excellent | Excellent |
| Consistency | Excellent | Poor | Fair | Excellent | Fair |
| Safety | Good Except for Overhead Signs | Excellent | Good Except for Overhead Signs | Good Except for Overhead Signs | Fair |
| Ease (Simplicity) | Good Except for Overhead Signs | Good | Good Except for Overhead Signs | Good for Signs $\leq$ 14 ft | Fair |
| Time/Measure | 5-10 min | 1 min | 10-20 min | 2-10 min | 10-30 min |
| Potential Sources of Error | | | | | |
| Environment | No | Yes | Yes | No | Yes |
| Vehicle | No | Yes | Yes | No | Yes |

Figure 3. Comparison of five methods for measuring nighttime sign performance.

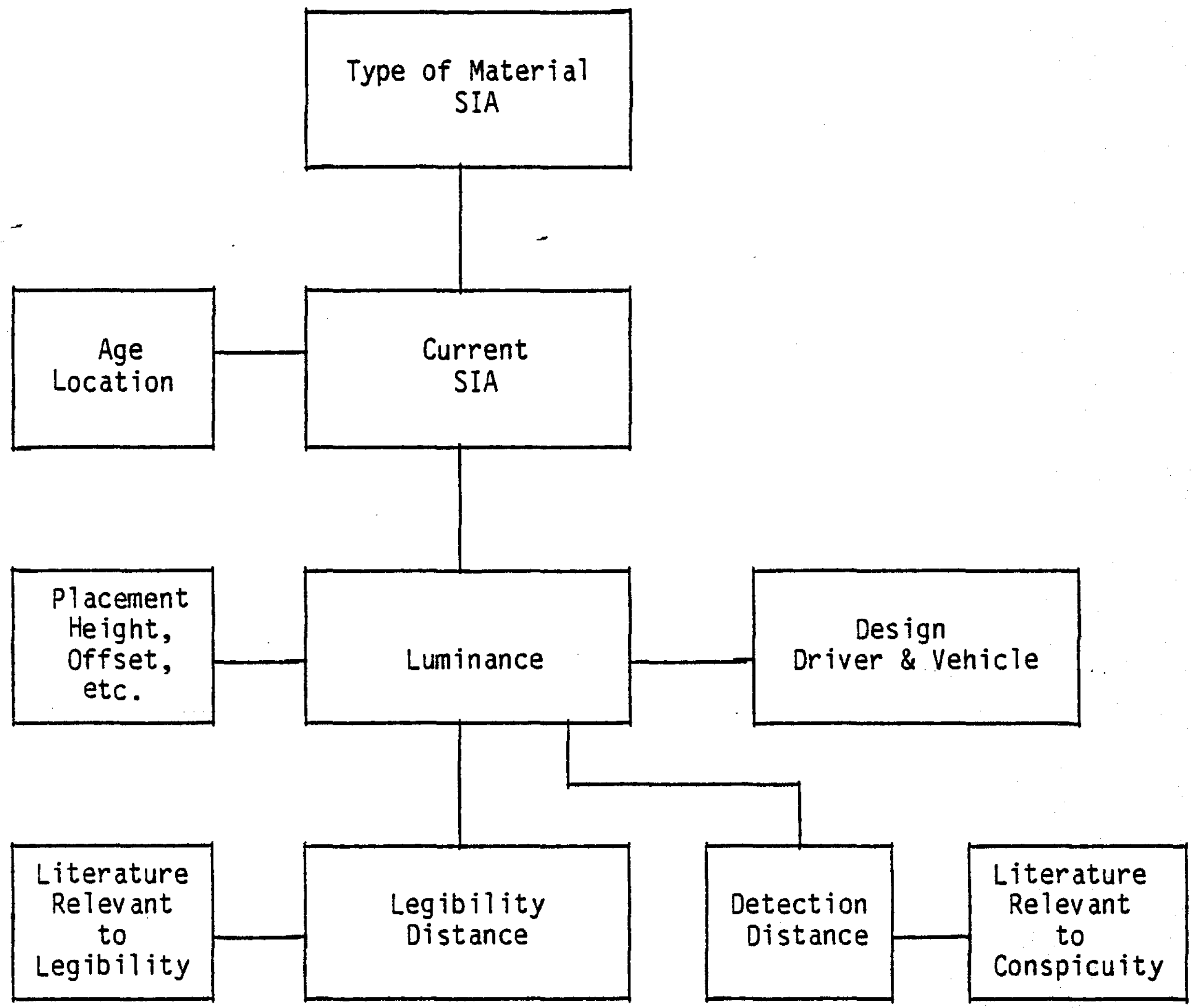



Figure 4. Paradigm for prediction of various measures of retroreflective sign performance.

| Measure | Method | Effect on Model |
|---|---|---|
| Original Specific Intensity | Easiest to obtain measure with retroreflectometer before installation in field | Greatest error in model--effects of deterioration, available luminance, and legibility must be predicted |
| Recent Specific Intensity | Requires measurement with retroreflectometer in field--particularly difficult for overhead signs | Greater accuracy than when original SIA is used because effects of age and environment are accounted for empirically |
| Available Luminance | Difficult to measure--requires photometer mounted in vehicle, stopped in lane of travel | Greater accuracy for model because effects of sign position, geometry, and ambient light are accounted for empirically |
| Legibility Distance | Requires distance measuring instrument and multiple subjects and replications | Poor generalizability (unless multiple subjects and replications are used) because of variance from uncontrolled factors, e.g., glare and individual differences |

Figure 5. Alternative measures of retroreflective sign performance.

in appendix A. Other relevant reviews were recently conducted by Sivak and Olson (1985) and Gordon (1984).[9,10] Jacobs et al. (1975) provide data relevant to the legibility of symbol signs.[11] For a discussion of luminance requirements for sign conspicuity, see Mace et al. (1985).[7] A model to estimate required luminance for a specified legibility requirement using data from the open literature is reported in the next section of this report.

If it is not feasible to either measure or estimate photometric sign luminance with field inspection, a computer model may be used to predict the available photometric luminance from a measure of specific luminance (either predicted or empirically obtained). Such a model was developed and is described in the next section.

Finally, if one cannot obtain a recent measure of a sign's specific luminance, this also may be estimated from a measure of the original SIA, type of sheeting, and age. A simple sign deterioration model is also included in the overall system described in the next section. The plethora of variables known to affect deterioration were not included for reasons related to validity discussed in appendix B, and because it was considered unlikely that such information would be available to a computerized system.

## 2. Situational Factors Differentiating Replacement Needs

Olson and Bernstein (1977) provided legibility distance for signs with varying contrast and reflectivity.[8] If one can express the legibility requirement of a sign in feet per inch of letter height, the data provide a basis for developing standards to meet legibility needs. Olson and Bernstein's data provide a basis for developing differential standards based upon a number of situational factors. The situations considered in their report were:

- Sign placement--roadside (8 ft high, 12 ft offset)(2.4 m, 3.7 m)
  --overhead (20 ft high, 0 offset)(6.1 m)
- Road curvature--tangent, 2 degrees right, 2 degrees left
  --level, sag, crest (A = 8 percent)

Their data represent 85th percentile scores for young drivers with normal vision. Several observations we have made from a review of their data for signs with nonreflective legends are as follows:

- With respect to grade, the crest situation improved the legibility of overhead signs by about 25 percent (5 to 9 ft/in)(0.6 to 1.1 m/cm), while the sag situation decreased legibility by less than 10 percent (2 or 3 ft/in)(0.24 or 0.36 m/cm).
- Right hand curves improved legibility by 1 or 2 ft/in (0.12 or 0.24 m/cm), while left hand curves reduced legibility by 1 or 2 ft/in (0.12 or 0.24 m/cm).
- Within a situation, the range of SIA from 250 to 5 produced 25 percent to 50 percent decreases in legibility distances.
- Placing signs overhead decreased legibility by 10 to 20 percent from the level, tangent roadside placement.

These observations suggest that designing luminance standards for the tangent with level grade condition provides a reasonable representation of what would be empirically experienced. We noted that the detrimental effects of grade and curvature were greatest with SIA at extremely low levels. It is therefore possible that an interaction might exist which would dramatize their effects with older drivers with contrast sensitivity problems. From a practical standpoint however, it is desirable to leave the conditions created by grade and curvature out of the specification of luminance standards. This is desirable because such information is generally not readily available and not likely to be a part of computer-based sign inventories. Normal variation can be accommodated by a safety factor built into the standards. Extreme situations will be handled by sign placement or supplemental signing.

Sign placement is a situational variable which is generally available in any sign inventory: therefore, given the large effect placement can have, differential standards should be applied to different placements. In fact, the placement variable can be elaborated to account for extreme offsets and curvature. In recommending luminance standards for replacement, Sivak and Olson (1985) discriminated four placements: Right-shoulder, right-guide-sign, overhead, and left-mounted.(9)

### 3. Sign Classification

Another attribute of signs which has not been explored, but which provides a meaningful basis for differentiating sign reflectance standards, is the classification of signs according to the need for reflectivity. The attempt to grade signs with respect to legibility requirements, i.e., signs which require 30, 40, 50, and more than 50 feet of legibility per inch (3.6, 4.8, 5.9 m/cm) of letter height, is one example of the usefulness of sign classification. This type of classification can nominally sensitize standards to driver needs differentiated with respect to number of lanes, average daily traffic, speed, sign placement, and even sign design. For example, one can require more feet per inch, and therefore greater reflectivity, from signs in situations with high speed or high volume or multilane roads. One can nominally classify symbol signs as 30 ft/in (3.6 m/cm) and similar alphabetic signs as 50 ft/in (5.9 m/cm). That is, symbol signs require less luminance and therefore lower values of feet per inch because symbols have greater recognizability than the letters typically used on an equivalent size sign. One can classify signs requiring vehicle maneuvers as 50 ft/in (5.9 m/cm) or greater, while signs requiring no response as 40 ft/in (4.8 m/cm), and signs requiring no decision as 30 ft/in (3.6 m/cm). Signs designed to enhance legibility, such as the STOP sign, could be equated with signs requiring 30 ft/in (3.6 m/cm), and the speed limit sign, because of its large numerals, 40 ft/in (4.8 m/cm).

The effects of motivation and uncertainty on the need for conspicuity were discussed in the first section of this report. If we were to establish standards with respect to drivers' needs for conspicuity, a simple classification system which might be appropriate is shown in figure 6.

In this classification scheme, uncertainty is related to driver expectancy and motivation is related to the need for information and therefore the extent to which it is likely to be actively sought. In the figure, for example, the cell representing passive information search and unexpected knowledge of events would be used for signs related to a roadway hazard. That is, the driver is not actively searching for the sign, and the hazard is unexpected.

Extent to which information is sought (driver motivation):

| Driver knowledge of upcoming events: | Active | Passive |
|---|---|---|
| Known | Low | None |
| Unexpected | Med | High |

Figure 6. Different levels of sign luminance required for situations with different levels of motivation and expectancy.

One other basis for classification is to identify the criticality of a sign's message. Criticality classification was implemented in the system to be described in the third section of this report. The field evaluation of the system detailed in the fourth section reports that this level of classification is a basis for judgments by those responsible for maintaining traffic signs. It was not surprising, however, that significant differences existed among raters. A computerized system allows consistent application of the rules, and eliminates the source of variance which highway personnel introduce to the task.

The classification used in this system is based upon the broad recommendations in the <u>Pennsylvania Department of Transportation Sign Foreman's Manual</u> (1983):

> Routine maintenance schedules must be adjusted to give priority to damaged or missing signs that could be considered emergency. Emergency repairs should be with priorities as follows:
>
> 1. STOP, YIELD, and ONE-WAY signs.
> 2. Regulatory and warning signs indicating hazards that prohibit or require an action or an adjustment in the traveled path.
> 3. Other regulatory signs.
> 4. Other warning signs.
> 5. Guide signs.
> 6. General information signs and delineators.

> Within the regulatory signs, priorities should be given to those signs that prevent a conflict between vehicles. In the warning sign priority, preference should be given to those signs that warn of a reduction of roadway width or number of traffic lanes, curves, narrow or one-lane bridges or underpasses, or changes in traffic patterns.(12)

It is clear from the above discussions that there are a number of dimensions that merit consideration in the design of a decision support system for maintenance of sign luminance standards. It is also clear that such a system must be sufficiently flexible to accommodate different types of data availability and a range of data quality with respect to any given dimension of concern. A system which can accommodate the differences that exist in the field can be useful from the start and will improve in utility as the quality and quantity of sign inventory information improves.

DECISION SUPPORT FOR SIGN STANDARDS AND MAINTENANCE

A decision support system was developed using an office microcomputer to provide assistance to management, operations, and research and design officials concerned with retroreflective traffic signs. The system is designed either to interface interactively with the user or to be used with an automated sign inventory. Using information from one or more models and data bases, the system will answer questions about driver requirements for sign brightness and the degree to which specific signs satisfy those requirements. The major data bases and models within the system are:

- Sign Inventory.
- Sign Dictionary.
- Road File.
- Sign Deterioration Model.
- Sight Distance Model.
- Available Luminance Model.
- Required Luminance Model.

1. <u>System Description</u>

In the batch (noninteractive) mode the system can provide the required legibility or recognition distance for each sign in an automated sign inventory. These estimates consider the length of sign message, the complexity of the driver decision, and the type of manuever the driver must make in addition to the likely approach speed. The system also provides the luminance required for legibility, or recognition, and detection, as well as an estimate of the luminance available at any specified distance from a sign. The available luminance (candelas per square foot) is based upon the best estimate or most recent measurement of the sign's reflectivity and considers placement, sign height, number of lanes, and lane width. Default values for vehicle and headlamp design are provided.

a. Files and Models

The sign inventory may be real or fictional. A fictional inventory can be created, for example, to test the economic impact of alternative sign replacement strategies; to investigate the effects of sign placement; or to evaluate the effects of symbol versus alpha signs. Explanation of the sign inventory and other files, as well as of the models, follows:

(1) Sign Inventory. The primary data file used is the sign inventory file, which contains information on each sign. In addition to the sign code and roadway code, each sign inventory entry includes sign-specific information such as location of the sign, physical measurements, and installation and last inspection dates. Location is indicated by roadway code, segment start point, position (right, left, median, overhead), and offset from the side of the road. Physical measurements include the dimensions of the sign, the sign blank materials (aluminum, steel, wood), the sheeting type and manufacturer, and reflectivity (SIA). Another field in each record allows recording of recommended actions, such as cleaning, replacement, or relocation of the sign. Space is allowed for the unique messages that appear on guide signs.

(2) Sign Dictionary. To minimize storage and data entry time and to reduce the possibility of error, unchanging sign characteristics such as colors, class, and message complexity were stored in a separate file called the sign dictionary. Each inventory record contained a sign code, generally the MUTCD code, and this code was used to index the dictionary. A dictionary record contains the legend for the sign, an indication as to the legend type (alpha or symbol), the shape of the sign (square, rectangle, triangle, octagon, etc.), letter stroke-width-to-height ratios, and a list of generally used sizes for the sign. Additionally, required driver action, sign criticality, maneuver location, time required to read or recognize the sign message, decision complexity, and sign class are stored for each sign. Possible values are shown in figure 7.

(3) Road File. Information which is constant for a given roadway section is stored in the road file and referred to indirectly by including a roadway identifier in the sign inventory file. This information includes an indication of one- or two-way traffic, number of lanes, lane width and typical freeflow traffic speed and volume. Default values for sign placement and

| Entry | Code | Meaning |
| --- | --- | --- |
| Sign Criticality | 1 | Stop required |
| | 2 | Other than stopping action required (e.g., lane change) |
| | 3 | Regulatory sign (e.g., speed limit) |
| | 4 | Warning (e.g., curve ahead) |
| | 5 | Guide sign |
| | 6 | Information only |
| Maneuver Required | 0 | None |
| | 1 | Stop |
| | 2 | Lane change |
| | 3 | Reduce speed |
| | 4 | Turn |
| | 5 | Yield |
| Maneuver Location (if required) | 0 | After passing the sign |
| | 1 | Before passing or on reaching the sign |
| Reading Time | - | Number of seconds needed to read the sign |
| Decision Complexity | 0 | No decision required--information only |
| | 1 | Simple decision |
| | 2 | Complex decision |
| Sign Class | 1 | Maneuver required (e.g., lane drop) |
| | 2 | Other than maneuver response required (e.g., TURN OFF 2-WAY RADIO) |
| | 3 | Decision only required (e.g., exit in 2 miles) |
| | 4 | Recognition only required (e.g., milepost) |

Figure 7. Illustrative sign dictionary codes.

height are included, to be used if such information is not available from the sign inventory. A sign deterioration factor in each roadway entry is used to indicate the relative rate at which signs age (deteriorate) along that section; for instance a roadway serving an industrial plant might have a higher rate due to smoke accumulation than a sparsely travelled shaded road. Visual complexity is also coded for each road segment, ranging from low, such as most rural roads, to high, such as would be found in a downtown location where illuminated advertising and other detail makes the task of finding a roadway sign more difficult.

The three files described above make up the data base on which the software operates. Models in the software use data items from these files to compute the SIA, available luminance, or luminance deficiency. These can be used as replacement criteria by a data base query subprogram. Each of the models and the data base query program for sign selection and replacement cost are described below. Figure 8 shows how the various models work together to produce an estimate of luminance deficiency.

(4) Sign Deterioration Model. Several factors affect the useful life of retroreflective material. The original sheeting can vary in both initial reflective performance and durability. The goal in the development of a deterioration model was to take into account as many of these factors as possible in estimating the reflective property (SIA) of signs in the data base. The relevant variables and problems in developing a valid deterioration model are documented in appendix B.

The deterioration model should take into account sheeting type, reflective properties of new material, normal aging rates, and special factors. To determine typical aging rates due to exposure for various sheeting materials, manufacturer's specifications and expert opinion were compiled and average rates were generated for use by the deterioration model. These rates reflect the number of years of use which can normally be expected from sheeting material before its reflectivity (measured by SIA) deteriorates to 50 percent of reflectivity for new material. For the widely used engineering grade sheeting, a useful life of 7 years was used, while high intensity

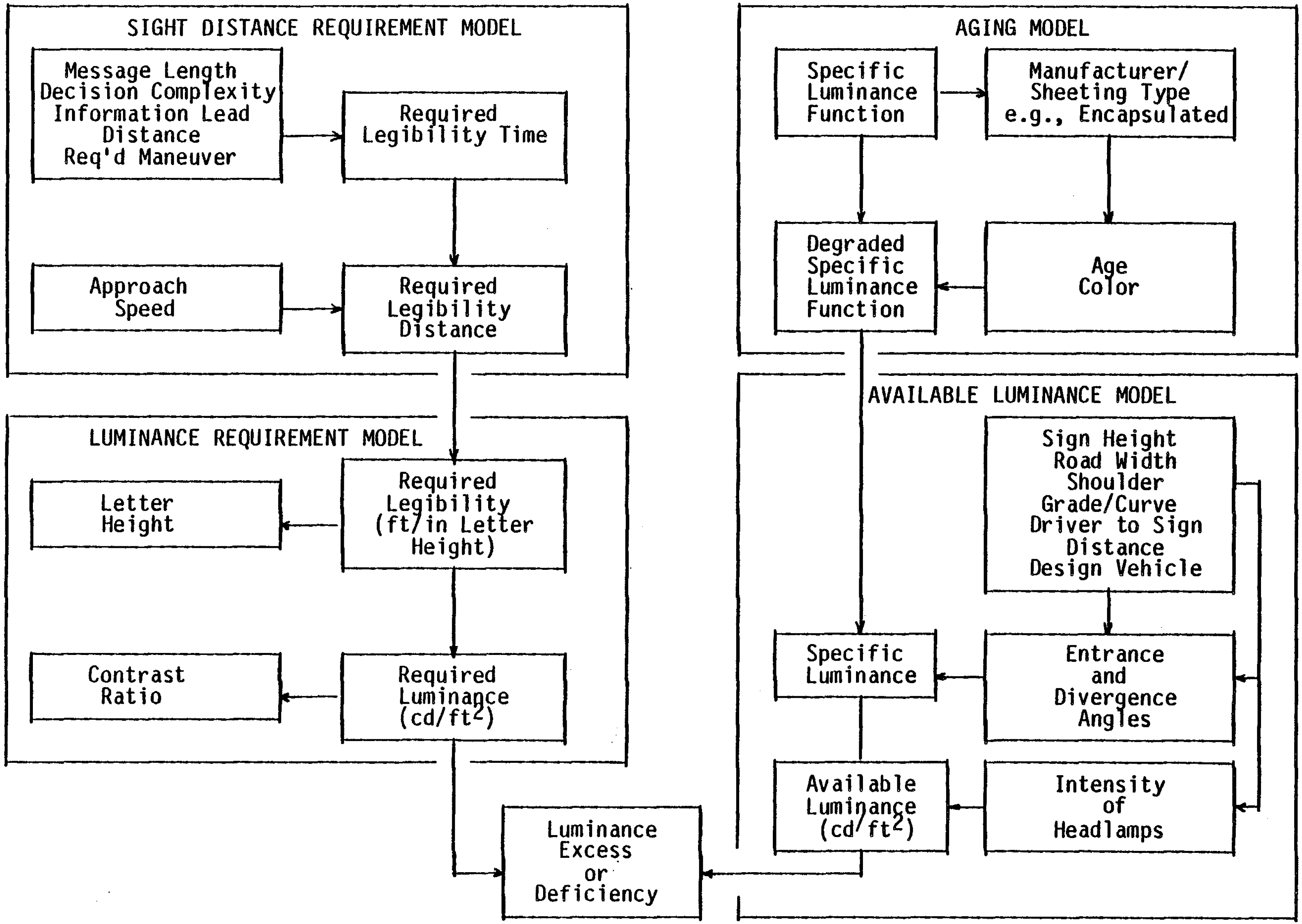



Figure 8. Logic flow of models within sign maintenance system.

sheeting was expected to last 12 years. Based upon weathering data from the 3M Corporation, the aging rates are applied to manufacturer's specifications of SIA in a linear fashion; engineer grade sheeting which has an SIA of 70 when new will be estimated to have SIA of 35 after 7 years, and to be totally dark after 14 years of use.[13]

Special factors such as extremes of exposure, chemicals not normally present and the like, which affect useful sign life, are left to the user to enter via the degradation factor included in the road file for each section of roadway. This factor, which has a value of 1 for a typical section is divided into the standard life span to determine a local value; high intensity sheeting useful life would change from 12 years to 8 on a roadway section with degradation factor of 1.5. Roadway degradation factors must be determined through experience and individual judgment; no modeling exists for them.

The aging model incorporated into the system uses only three variables: sheeting type, years of exposure, and the roadway degradation factor. The sheeting type determines the typical useful life, which is divided by the degradation factor and then applied linearly over the number of years of exposure. Other variables as mentioned above were not included, both because they have a poor correlation with sign degradation (see appendix B for more detail), and because they would make the system difficult to use and therefore unlikely that agencies would insert this information into a data base.

(5) Sight Distance Model. One possible criterion for sign replacement is a comparison of the luminance available from a given sign with that required for safety. Models for both available and required luminance were incorporated into the software package and are described subsequently. Both of these models require an estimate of the required legibility distance or recognition distance.

A decision sight distance model based upon the principles and literature summarized by Perchonok and Pollack (1981) was included in the system to determine where any sign would be detected and where it should be legible.[14] It is a linear model containing components for maneuvering the vehicle, responding, decision making, reading or recognizing the message, and finding the sign among the visual clutter. The model provides for varying detection distance, depending on visual complexity of the scene, but because of the paucity of data in the literature, this function was not implemented.

The model obtains values from the sign inventory, roadway file, and sign dictionary, and computes the required distance according to the model's rules and formulas. Information obtained from the sign inventory includes sign code, placement, type of sheeting, and size. Information obtained from the roadway file includes sign height, offset, approach speed, number of lanes and volume. The sign dictionary provides information on letter height, color, message length, decision complexity, and type of maneuver required. All information needed to compute detection and legibility, or recognition, distances is included in the reference cited above.[14] Examples for two signs are given in tables 2 and 3.

The surround visual complexity affects the time required by a driver to detect a sign, because of distraction and fixation on surround details. This time was called fixation time, and has a value of 2.15 seconds for more visually complex surrounds, and 0.35 seconds for less complex surrounds. Given this wide range, it would perhaps be useful to eventually include a midrange value.

Message complexity indicates the amount of time required to understand the sign's message, after the sign is located. The sight distance model simply uses the amount of time, in seconds, required to read, or recognize, the sign.

Decision complexity was coded as the number of possible legal responses to a sign. A lane restriction sign (i.e., left arrow, ONLY), for example, has a decision complexity of 1--the possible alternatives are to proceed in the indicated lane, or in some other lane. The single choice is between staying in the turn lane or shifting to a through lane. A STOP sign, on the other hand, allows for no choice, and so has a decision complexity of zero.

Depending on the type of response asked by a sign, required legibility or recognition distance can be affected by traffic volume. If, for instance, a lane change is demanded, such as indicated by a lane-drop sign, execution of the response (the lane change) will take more time in heavy than in light traffic and therefore requires earlier availability of information. For other response types such as a stop, volume does not play a role in determining maneuver time. Still other signs do not require a maneuver, and this component of total distance is not used. Table 1 table combines the effects of decision complexity, volume, and traffic speed, giving a decision time.

Table 1. Decision time.

| Speed (mi/h) | Decision Complexity (number of choices) < 2 Time (s) | 2 Time (s) | > 2 Time (s) | |
|---|---|---|---|---|
| < 45 | 0.5 | 0.5 | 2.5 | low volume |
| 45 | 0.5 | 2.5 | 2.5 | low volume |
| > 45 | 0.5 | 2.5 | 2.5 | low volume |
| < 45 | 0.5 | 0.5 | 2.5 | high volume |
| 45 | 0.5 | 2.5 | 4.5 | high volume |
| > 45 | 2.5 | 4.5 | 4.5 | high volume |

Note: 45 mi/h = 72 km/h.

Typical traffic speed is used to convert time required for the various components (detection, legibility or recognition, response, maneuver) into distance traveled. Component distances are then summed into required detection distance. By way of example, tables 2 and 3 show the components and the required detection distances for two types of signs.

(6) Available Luminance Model. Calculation of the luminance available from a sign under varying conditions of sign location and placement, source illumination, and observer position is modeled as suggested by Olson and Bernstein (1977).[8] The model first calculates the illuminance on the sign from a light source, then the luminance returned to the observer. This model has data stored representing luminance intensity of a headlamp in a range of

Table 2. Required detection distance for the STOP sign.

| Initial Speed | | Detection | Recognition | Decision | Response | Maneuver | Total Distance |
|---|---|---|---|---|---|---|---|
| mi/h | ft/s | 2.15 | 2.0 | 0.5 | 1.0 | > 0 mi/h | |
| 65 | 95.4 | 205 | 191 | 48 | 95 | 569 | 1,108 |
| 60 | 88.0 | 189 | 176 | 44 | 88 | 484 | 981 |
| 55 | 80.7 | 174 | 161 | 40 | 81 | 407 | 863 |
| 50 | 73.4 | 158 | 147 | 37 | 73 | 337 | 752 |
| 45 | 66.0 | 142 | 132 | 33 | 66 | 272 | 645 |
| 40 | 58.7 | 126 | 117 | 29 | 59 | 215 | 546 |
| 35 | 51.3 | 110 | 103 | 26 | 51 | 164 | 454 |
| 30 | 44.0 | 95 | 88 | 22 | 44 | 121 | 370 |

Table 3. Required detection distance for class 3 signs (response and maneuver not required).

| Initial Speed | | Detection | Recognition | | | Decision | | | Total Distance | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mi/h | ft/s | 2.15 | 2.0 | 3.0 | 4.0 | 0.5 | 2.5 | 4.0 | Low | Med | High |
| 65 | 95.4 | 205 | 191 | 286 | 382 | 49 | 239 | 382 | 273 | 558 | 969 |
| 60 | 88.0 | 189 | 176 | 264 | 352 | 44 | 220 | 352 | 251 | 515 | 893 |
| 55 | 80.7 | 174 | 161 | 242 | 323 | 40 | 202 | 323 | 229 | 472 | 829 |
| 50 | 73.4 | 158 | 147 | 220 | 294 | 37 | 184 | 294 | 210 | 440 | 746 |
| 45 | 66.0 | 142 | 132 | 198 | 264 | 33 | 165 | 264 | 188 | 386 | 670 |
| 40 | 58.7 | 126 | 117 | 176 | 235 | 29 | 147 | 235 | 167 | 344 | 596 |
| 35 | 51.3 | 110 | 103 | 154 | 205 | 26 | 128 | 205 | 147 | 300 | 520 |
| 30 | 44.0 | 95 | 88 | 132 | 176 | 22 | 110 | 176 | 125 | 257 | 447 |

Note: 1 ft = 0.305 m; 1 mi = 1.61 km.

directions. The specific data used represents a pair of halogen headlamps aimed according to the Society of Automotive Engineers' (SAE) specifications. Using measurements of sign offset and height acquired from the sign inventory and road file, the distance from the light source (vehicle) to the sign derived by the sight distance model, and trigonometry, a calculation of the angle at which light from the headlamps leaves the headlamps to get to the sign is made to determine light intensity in the direction of the sign. Light intensity and distance to the sign determine illuminance on the sign. This illuminance, multiplied by the specific luminance function, gives the available luminance.

The specific luminance function was derived from data received from 3M Corporation, a manufacturer of sheeting materials. The only complete data available was for engineering grade sheeting; this function is simply shifted up to account for high intensity grade. The specific luminance function is additionally modified by the aging model, which generally shifts the values down. It is a function depending on the angle the incident light makes with the sign surface, and the angle light leaving the sign toward the observer makes with the incident light beam. These angles are calculated by the model from the particular geometrics of each situation, and certain constants representing measurements on a "typical" car.

Reported available luminance varies with the parameters to the model, but not always in the direction one might expect. For instance, at a distance of 200 ft (61 m), a sign at a 4-ft (1.2 m) offset from the road has a lower luminance than the same sign at a distance of 400 ft (122 m), both because headlamp aim directs a brighter part of the beam toward the sign at the greater distance, and because the specific luminance function is greater as the angle between incident light and exiting light decreases. These factors overcome the fact that light intensity from the headlamp is attenuated to a greater extent at the greater distance; at some point, however, attenuation takes over as the dominant factor with further distance increases.

(7) Required Luminance Model. Formulas were developed as a result of the review of current literature relating legibility distance to luminance.

Legibility distance is in units of feet away from a sign to inches of letter height on the sign; a legibility distance of 50 ft/in (5.9 m/cm) means that a sign with 4-in (10.2 cm)-high letters can be read from a 200-ft (61 m) distance. In the software package, required legibility distance is calculated from the sight distance model output and the letter height of the sign in question, as stored in the sign dictionary; if 300 ft (91 m) are required for reading and reacting to the sign, and the sign contains 5-in (12.7 cm) letters, a legibility distance of 60 ft/in (7.2 m/cm) is computed.

Consideration was given to developing separate luminance models for fully reflectorized signs and signs having either the background or legend non-reflective. A review of the literature, however, did not support the need for such a model. The colors in a fully reflectorized sign (in the range of intensity where replacement should occur) deteriorate without any bias to one or the other color. Therefore contrast is essentially established by the materials at the time of manufacture. Olson and Bernstein (1977) provide data which show that, while manipulating contrast to extreme levels produces significant changes in legibility distance, within the contrast range which characterizes most highway signs, legibility is only minimally affected by luminance changes in the less bright (i. e., background) material.[8] Changes are typically in the range of only 2 to 5 ft/in (0.24 to 0.6 m/cm) of letter height. While a change of 60 ft (18 m) in legibility for a sign with 12-in (30.5 cm) letters might be worthwhile noting if one were designing a sign, the system overhead required to factor such information into an automated sign replacement system would not be worth any reasonable expectation of savings which such precision might attempt to obtain.

The model chosen as a reasonable representation of much conflicting data reviewed in appendix A was an exponential function of required legibility distance; for an increase in legibility distance of 10 ft/in (1.2 m/cm), required luminance had to increase by a factor of 3.

b. Interaction of User, Files, and Models

The final portion of the software package ties together the data files and model results to produce a list of signs recommended for replacement. The system is capable of using the output of the various models by selecting signs for replacement based upon complex decision rules with criteria related to age, reflectivity of sign material, and an estimate of the luminance excess or deficiency with regard to driver requirements. Different criteria may be specified with reference to a variety of sign classifications. Sign classifications may be defined with regard to sign type, material, color, criticality, or location. The system automatically assigns a criticality level to each standard sign, but to be responsive to local conditions the user may direct the system to respond to different signs or sign classifications as if they had a different criticality level. An estimated replacement cost is provided for signs selected by any decision rule. Using a "what-if" procedure, one may evaluate the budgetary impact of different replacement schedules. For example, one could determine the cost of replacing all signs greater than 12 years old, regulatory signs which had reflectance below 50 SIA, and critical signs whenever available luminance at the required legibility or recognition distance was less than 120 percent of the luminance drivers require. Signs can also be selected based on combinations of values in the general categories of location and sign type. For instance, to select all STOP signs on routes 28 and 30 installed over 5 years ago, one would select from the categories of location, age, and sign type.

All of the dimensions queried can be combined in a variety of ways and any sign selected by any one combination will be included in the selected subset, so a set could include all regulatory signs over 5 years old with a luminance deficiency, plus all warning signs over 7 years old with a more severe deficiency, plus all signs over 10 years old regardless of other factors. The following paragraphs describe the selection criteria in more detail.

Location is the route or roadway segment on which a sign is situated. The route identifier, included in each inventory record, may be used to select signs if this option is chosen. Age of a sign, defined as the amount of time the sign has been in the field, may also be used as a selection criterion.

Signs may be selected by type in several ways: by criticality, general category, specific category, or exact code. Criticality of a sign can be one of four levels; a STOP sign is at the highest level, and a route marker is at the lowest. Signs with criticalities equal to, less, or greater than a specified value can be selected (the system references the sign dictionary, which contains the criticality level for each sign type). Selection by general or specific category is done by specifying the necessary letters of the MUTCD code: R for regulatory, W for warning, etc. More specific categorical selection can be achieved by specifying more of the MUTCD code; for example, the specification "RØ2" will select the speed series of regulatory signs, including speed limit, speed zone, and reduced speed signs. If more precision in selection is desired, one can simply indicate up to 20 specific sign codes to be searched.

Signs may be selected based upon reflectivity using the values of SIA recorded from field observations that are stored in the sign inventory. While all inventory records may not have measured SIA available, those that do could be used as an indicator of the SIA of similar signs of the same age. Selection can be made by comparing a criterion SIA with recorded SIA, and signs with SIA lower than the criterion value will be selected. Different criterion values can be used for the different sign placements: right, left, median, and overhead. Overhead signs, for instance, must be more reflective to achieve the same brightness as signs on the right, because the illumination they receive from headlamps is much lower.

Luminance deficiency is related to reflectivity, but it attempts to take into account sign placement and road geometry on the approach to the sign. This is done by using output from the models for required legibility or recognition distance, available luminance, and required luminance. If the estimated available sign luminance is never greater than that required for legibility or recognition over a range of distances, beginning at the required legibility or recognition distance, that sign can be classified as luminance-deficient. A range of distances must be considered because available luminance actually can increase at greater distances. Even though the illumination source (the headlamps of a car) is further away, the retroreflective property of signing material makes for higher luminance at greater distances because light is being reflected at a smaller angle; also, a different (perhaps higher) intensity of light is supplied by the headlamps in the direction of the sign. Required luminance is a simpler function--it always increases with distance. In processing, the model looks for the best case: that distance at which available luminance is largest with respect to required luminance (where their difference is greatest). The minimum distance used by the model is that determined by the decision sight distance model to be required for legibility or recognition. Once the best-case available and required luminances are computed, the query subsystem selects signs for replacement based on the amount of luminance excess or deficiency.

2. Who Might Use This Type of System?

There are at least three distinct types of users who could benefit from access to this type of system; these users will be referred to as management, maintenance operations, and research. Management may use the system in a number of ways. First, the system may be used to forecast budget requirements for sign maintenance by projecting different sign inventories for the future. The most immediate management use would be to evaluate the cost impact of different sign replacement schedules or strategies on sign maintenance budgets. Finally, the system provides a systematic and efficient model of sign maintenance which would have value in tort liability cases. That is, if an agency has a program to identify potentially deficient signs and to evaluate and replace such signs as budgetary constraints permit, they will stand on much firmer ground should litigation related to sign luminance occur.

In maintenance operations, the system can be used to assist in both the maintenance and evaluation of signs. It can provide a list of signs which need replacement or which require inspection according to any decision rule selected by management. This list can be organized by sign type or location and could be made to interface with a system for generating work orders.

Using the system interactively, one may explore alternative methods of satisfying driver needs. The system may help find ways of reducing driver requirements for luminance (e.g., symbol messages) or ways of increasing the luminance available (e.g., lower sign height or increased reflectivity). A user may also work interactively with the system to answer questions concerning the influence of different variables on driver requirements and sign luminance. For example, one might ask how changes in road width, sign placement, or reflective materials would change the luminance available at the distance the driver must detect or read a sign. Or, a user might be interested in how changes in message length, sign size, or approach speed affect the required legibility distance and the required luminance for the needed legibility.

## FIELD EVALUATION

The purpose of this task was to collect empirical data which could provide credibility to the replace and no-replace decisions generated by the sign management system. This task represents an evaluation of some of the models discussed in the previous section. The term evaluation rather than validation is used purposefully. Validation would require a test of the correctness of the sign replacement decisions which would suggest a cross validation and therefore replication of much of the research which contributed to the models. The goals of evaluation are more consistent with the scope and purpose of this research. Sommer (1977) provides some distinction between research and evaluation.

> Although research and evaluation complement one another, it is important to realize that the generation of new knowledge (research) does not require judgmental statements and that evaluation does not require the generation of new knowledge so much as it does a quantification and costing of factors already identified as important and relevant.([15])

Before developing an evaluation plan, it was important to critically identify what characteristics of the model should and could be evaluated. The sign management system began as an attempt to create a model which would permit a prediction of sign quality based upon knowledge of a sign's age, material, and situational factors which effect both deterioration and available luminance. Replacement standards should be based upon different luminance criteria for signs in different situations with different levels of criticality.

The scope of this research required that the model be built from data available from previous research. New research was not undertaken and sufficient data were not available to build a reliable model which would determine deterioration and predict current levels of luminance. Neither could a model be built that would predict the legibility, recognizability, or detectability of all signs in any one situation or of any one sign in all situations. The inadequacies of the literature are documented in appendixes A and B. Large variances, inconsistent results, and incomplete experimental designs were typical of the luminance requirements studies. Since the only available research which provided luminance requirements for detection was limited to yellow-diamond warning signs (Mace et al., 1985), detection requirements could not be the principal dimension of system evaluation.[7] The system, however, can be easily modified to base replacement on luminance requirements for detection when additional research provides the necessary data.

Since a model to predict the luminance required for legibility was included in the system, this task attempted to address the reasonableness of the decisions about replacement based upon available luminance as a percent of luminance required for legibility. These decisions need to be evaluated with respect to sign placement, color, and symbol-no symbol messages to determine if their reasonableness is limited to specific signs or situations. Because of incompleteness in the literature, it may be that reasonable results will not be obtained for symbol signs, or across different letter styles, or across different ambient environments.

From a practical perspective, performance standards may be easier to implement if expressed as specific intensity per unit area (SIA). Sivak and Olson (1985), addressing the question of replacement luminances for traffic signs, provide different levels of SIA for different geometric situations as the criteria for sign replacement.[9] In this task we tested the reasonableness of the replacement levels suggested by Sivak and Olson and of alternative replacement levels using SIA. In addition to the geometric situations used by these authors, we imposed differential standards which reflect differences in sign criticality.

## 1. Experimental Procedure

The experimental procedure was to have knowledgeable subjects drive a test route and evaluate signs, making decisions whether to replace or not replace.

Subject drivers were asked to play the role of highway personnel involved in sign inspection. They were told to drive a specific route and maintain a comfortable speed, at or below the posted limit. They were to leave considerable lead distance and to slow down or stop if necessary to maintain it. They were to allow following vehicles to pass if their lights might interfere with the driving task. They were also to report a number of different events. The events reported included where they could identify the sign as the type of sign they were looking for, and where they could identify the sign message. They also assessed the adequacy of the sign's luminance using a 5-point scale and made a summary judgment of whether or not the sign should be replaced.

2. Independent Variables

The two major independent variables were sign criticality and sign reflectivity. Every sign in a computerized sign inventory was assigned a level of criticality as discussed in the previous section of this report. Almost every sign in the MUTCD and Standard Highway Signs was included in this dictionary.(1,16)

For purposes of selecting signs in this task, classification levels 3 and 4 were combined and levels 5 and 6 were combined. The experimental design therefore included signs from four levels of criticality.

Signs were selected to represent a range of reflectivity. The selection was made with regard to the amount of specific intensity. The levels of specific intensity bracketed the replacement levels recommended by Sivak and Olson (1985) for reflectorized white, yellow, and orange backgrounds of signs with black legends.(9)

To ensure the system's generalizability to different inventories of signs, additional independent variables which had to be sampled included placement, type of road, and color-shape. Sign placement was varied to include four levels:

- Right shoulder--5 ft to 7 ft high; 2 ft to 10 ft offset (1.5 m to 2.1 m; 0.61 m to 3 m).
- Shoulder guide--6 ft to 8 ft high; 16 ft to 24 ft offset (1.8 m to 2.4 m; 4.9 m to 7.3 m).

- Left shoulder--5 ft to 7 ft high; 2 ft to 10 ft offset (1.5 m to 2.1 m; 0.61 m to 3 m).
- Median--5 ft to 7 ft high (1.5 m to 2.1 m).

Road type was varied by including two-lane rural and four-lane with and without median. Both bright areas and dark rural areas were included.

In order to sample colors and shapes, black-on-yellow, black-on-white, and white-on-red signs were included in rectangular and diamond shapes. The unique shapes of the no-passing pennant and STOP sign were also included.

Because so many variables had to be tested, a complete factorial was out of the question. In fact, stratification on the variables of interest was difficult because of the constraint that all signs had to exist along a route that could be driven in a 2-hour period of time.

The signs included in the final sample are described in tables 4 and 5. Table 4 provides data from the sign dictionary of 25 sign codes used in the study. Table 5 provides data from the sign inventory of 66 signs.

3. Dependent Variables

The principal variable is the dichotomous judgment to replace or not to replace a sign. This variable was obtained empirically from each subject for each sign and analytically from the model using alternative measures of luminance. The specific alternative measures of luminance are described on page 48 of this section. An additional measure obtained from the subjects was the scale value of sign brightness. Recognition and legibility distances were also recorded, as were the averages for different placements.

4. Subjects

Eight subjects provided the empirical data for the evaluation study. Two subjects were Pennsylvania DOT traffic engineers whose normal activities involved judgments about sign replacement and the evaluation of sign brightness. Three subjects were township managers with responsibility for sign replacement, but without training as traffic engineers. The last three

Table 4. Signs used in the field evaluation.

| SIGN CODE | LEGEND | COLORS LEGEND | COLORS BACKGROUND | CRITICALITY | MANEUVER REQUIRED | READING TIME (SEC) | DECISION COMPLEXITY | SIGN CLASS |
|---|---|---|---|---|---|---|---|---|
| R 1-1 | STOP | WHITE | RED | 1 | 4 | 1 | 0 | 1 |
| R 2-1 | SPEED LIMIT | BLACK | WHITE | 3 | 2 | 1 | 0 | 1 |
| R 3-5 | lane control (arrow, ONLY) | BLACK | WHITE | 2 | 1 | 1 | 1 | 1 |
| R 3-6 | lane control (arrow) | BLACK | WHITE | 2 | 1 | 1 | 1 | 1 |
| R 3-9a | center lane left turn (arrows) | BLACK | WHITE | 1 | 1 | 1 | 1 | 2 |
| R 4-1 | DO NOT PASS | BLACK | WHITE | 2 | 0 | 2 | 0 | 2 |
| R 4-7 | keep right (symbol) | BLACK | WHITE | 2 | 0 | 1 | 0 | 3 |
| R 4-9 | ENTER HERE (arrow) | BLACK | WHITE | 3 | 0 | 2 | 1 | 2 |
| R 5-1 | DO NOT ENTER | RED/WHITE | WHITE | 1 | 2 | 2 | 1 | 1 |
| M 1-4 | US route marker | BLACK/WH | WHITE | 6 | 0 | 1 | 0 | 4 |
| M 1-6 | State route marker | BLACK/WH | WHITE | 6 | 0 | 1 | 0 | 4 |
| D 1-3 | destination sign | WHITE | GREEN | 5 | 0 | 3 | 0 | 4 |
| S 3-1 | SCHOOL BUS STOP AHEAD | BLACK | YELLOW | 2 | 0 | 2 | 1 | 3 |
| W 1-1 | turn (arrow) | BLACK | YELLOW | 2 | 0 | 1 | 0 | 2 |
| W 1-2 | curve (arrow) | BLACK | YELLOW | 2 | 0 | 1 | 0 | 2 |
| W 1-4 | reverse curve (arrow) | BLACK | YELLOW | 2 | 0 | 1 | 0 | 2 |
| W 2-1 | crossroads (symbol) | BLACK | YELLOW | 2 | 0 | 1 | 0 | 2 |
| W 2-2 | side road (symbol) | BLACK | YELLOW | 2 | 0 | 1 | 0 | 2 |
| W 2-4 | T-intersection (symbol) | BLACK | YELLOW | 2 | 0 | 1 | 0 | 2 |
| W 9-2 | LANE ENDS MERGE LEFT | BLACK | YELLOW | 2 | 0 | 3 | 1 | 2 |
| W13-1 | speed warning (advisory) | BLACK | YELLOW | 2 | 2 | 2 | 0 | 1 |
| W13-2 | exit ramp speed (advisory) | BLACK | YELLOW | 2 | 2 | 2 | 0 | 1 |
| W14-3 | NO PASSING ZONE (pennant) | BLACK | YELLOW | 2 | 1 | 2 | 1 | 1 |
| W14-5 | PLANT ENTRANCE | BLACK | YELLOW | 4 | 0 | 1 | 0 | 4 |
| W15-2 | WATCH CHILDREN | BLACK | YELLOW | 4 | 0 | 1 | 1 | 3 |

Table 5. Sign inventory for field evaluation.

| ID | MUTCD CODE | SIGN SIZE | LET SIZE | LOC | SYM | CRIT | SIA | LUMINANCES AVAIL | LUMINANCES REQ'D | LEGIBILITY DISTANCE |
|---|---|---|---|---|---|---|---|---|---|---|
| 23 | D 2- 2 | 72 X 24 | 6.0 | R | 0 | 5 | 68 | 4.044 | 4.178 | 173 |
| 37 | D 1- 3 | 120 X 60 | 6.0 | R | 0 | 5 | 281 | 12.983 | 13.709 | 385 |
| 53 | D 1- 3 | 120 X 60 | 6.0 | R | 0 | 5 | 291 | 13.761 | 13.709 | 373 |
| 35 | M 1- 4 | 30 X 24 | 12.0 | R | 0 | 6 | 30 | 1.780 | 0.261 | 152 |
| 36 | M 1- 4 | 30 X 24 | 12.0 | R | 0 | 6 | 49 | 2.324 | 0.535 | 197 |
| 42 | M 1- 4 | 30 X 24 | 12.0 | R | 0 | 6 | 21 | 11.528 | 0.360 | 199 |
| 55 | M 1- 4 | 30 X 24 | 12.0 | R | 0 | 6 | 21 | 11.528 | 0.360 | 199 |
| 01 | R 3- 5 | 30 X 36 | 6.0 | 0 | 1 | 2 | 24 | 0.081 | 5.299 | 580 |
| 03 | R 2- 1 | 24 X 30 | 10.0 | R | 0 | 3 | 1 | 0.039 | 0.662 | 269 |
| 05 | R 2- 1 | 24 X 30 | 10.0 | R | 0 | 3 | 1 | 0.039 | 0.662 | 269 |
| 11 | R 4- 1 | 24 X 30 | 6.0 | R | 0 | 2 | 1 | 0.038 | 10.355 | 128 |
| 12 | R 2- 1 | 24 X 30 | 10.0 | R | 0 | 3 | 89 | 4.606 | 0.649 | 92 |
| 14 | R 1- 1 | 30 X 30 | 10.0 | R | 0 | 1 | 29 | 1.504 | 0.637 | 165 |
| 15 | R 2- 1 | 24 X 30 | 10.0 | R | 0 | 3 | 139 | 6.859 | 0.807 | 389 |
| 19 | R 2- 1 | 24 X 30 | 10.0 | R | 0 | 3 | 112 | 4.440 | 0.807 | 389 |
| 26 | R 1- 1 | 24 X 24 | 8.0 | R | 0 | 1 | 78 | 4.262 | 0.900 | 165 |
| 28 | R 2- 1 | 24 X 30 | 10.0 | R | 0 | 3 | 136 | 6.711 | 0.807 | 389 |
| 29 | R 1- 1 | 24 X 24 | 8.0 | R | 0 | 1 | 58 | 2.560 | 1.227 | 165 |
| 30 | R 4- 1 | 24 X 30 | 6.0 | R | 0 | 2 | 88 | 5.094 | 5.531 | 165 |
| 39 | R 1- 1 | 30 X 30 | 10.0 | R | 0 | 1 | 57 | 2.703 | 1.119 | 272 |
| 41 | R 5- 1 | 36 X 36 | 5.0 | L | 4 | 1 | 33 | 17.270 | 0.927 | 403 |
| 43 | R 5- 1 | 30 X 30 | 4.0 | L | 4 | 1 | 169 | 88.441 | 0.927 | 403 |
| 44 | R 5- 1 | 36 X 36 | 5.0 | L | 4 | 1 | 82 | 3.846 | 1.176 | 403 |
| 46 | R 4- 7 | 24 X 30 | 25.0 | M | 1 | 2 | 24 | 1.317 | 1.846 | 99 |
| 48 | R 1- 1 | 30 X 30 | 10.0 | R | 0 | 1 | 52 | 2.845 | 0.724 | 353 |
| 49 | R 4- 9 | 24 X 30 | 25.0 | L | 1 | 3 | 83 | 5.892 | 5.764 | 165 |
| 50 | R 4- 7 | 24 X 36 | 25.0 | M | 1 | 2 | 60 | 3.566 | 0.994 | 99 |
| 51 | R 4- 9 | 24 X 36 | 25.0 | L | 1 | 3 | 24 | 1.704 | 5.764 | 165 |
| 56 | R 4- 7 | 24 X 30 | 25.0 | M | 1 | 2 | 106 | 58.189 | 1.846 | 99 |
| 57 | R 4- 9 | 24 X 30 | 25.0 | L | 1 | 3 | 68 | 4.827 | 5.764 | 165 |
| 58 | R 3- 6 | 24 X 30 | 0.0 | 0 | 1 | 2 | 25 | 0.483 | 13.709 | 745 |
| 59 | R 4- 7 | 24 X 30 | 25.0 | M | 1 | 2 | 69 | 3.631 | 13.709 | 99 |
| 61 | R 3- 5 | 30 X 36 | 6.0 | 0 | 1 | 2 | 84 | 1.536 | 13.709 | 745 |
| 63 | R 3- 9A | 48 X 60 | 0.0 | 0 | 1 | 2 | 82 | 4.330 | 5.850 | 165 |
| 64 | R 3- 5 | 30 X 36 | 6.0 | 0 | 1 | 2 | 22 | 0.425 | 13.709 | 745 |
| 65 | R 4- 7 | 24 X 30 | 25.0 | M | 1 | 2 | 100 | 0.038 | 0.261 | 99 |
| 66 | R 3- 6 | 30 X 36 | 0.0 | 0 | 1 | 2 | 46 | 0.193 | 13.709 | 745 |
| 09 | S 3- 1 | 30 X 30 | 5.0 | R | 0 | 2 | 44 | 2.224 | 13.709 | 128 |
| 17 | S 3- 1 | 30 X 30 | 5.0 | R | 0 | 2 | 42 | 2.295 | 11.246 | 165 |
| 02 | W14- 5 | 30 X 30 | 6.0 | R | 0 | 4 | 67 | 0.024 | 0.261 | 125 |
| 04 | W14- 5 | 30 X 30 | 6.0 | R | 0 | 4 | 5 | 0.190 | 12.623 | 115 |
| 06 | W15- 2 | 30 X 30 | 4.0 | R | 0 | 4 | 82 | 3.157 | 13.709 | 77 |
| 07 | W 1- 2 | 30 X 30 | 19.2 | R | 1 | 2 | 50 | 0.054 | 0.261 | 77 |
| 08 | W 1- 1L | 30 X 30 | 22.0 | R | 1 | 2 | 1 | 0.001 | 0.261 | 77 |
| 10 | W15- 2 | 30 X 30 | 4.0 | R | 0 | 4 | 81 | 3.119 | 13.709 | 77 |

Note: 1 in = 2.54 cm; 1 ft = .305 m.

Table 5. Sign inventory for field evaluation (continued).

| ID | MUTCD CODE | SIGN SIZE | LET SIZE | LOC | SYM | CRIT | SIA | LUMINANCES AVAIL | LUMINANCES REQ'D | LEGIBILITY DISTANCE |
|---|---|---|---|---|---|---|---|---|---|---|
| 13 | W 1- 1L | 30 X 30 | 22.0 | R | 1 | 2 | 24 | 1.224 | 0.689 | 99 |
| 16 | W 2- 1 | 30 X 30 | 40.0 | R | 5 | 2 | 8 | 0.408 | 0.689 | 99 |
| 18 | W 2- 4 | 30 X 30 | 35.0 | R | 5 | 2 | 27 | 1.450 | 0.420 | 99 |
| 20 | W 2- 4 | 30 X 30 | 35.0 | R | 5 | 2 | 1 | 0.044 | 0.543 | 99 |
| 21 | W 2- 1 | 30 X 30 | 40.0 | R | 5 | 2 | 46 | 2.345 | 0.689 | 99 |
| 22 | W15- 2 | 30 X 30 | 4.0 | R | 0 | 4 | 0 | 3.632 | 13.709 | 99 |
| 24 | W 2- 2 | 30 X 30 | 30.0 | R | 5 | 2 | 8 | 0.475 | 0.420 | 99 |
| 25 | W15- 2 | 30 X 30 | 4.0 | R | 0 | 4 | 30 | 1.611 | 13.709 | 99 |
| 27 | W 1- 4R | 30 X 30 | 20.6 | R | 1 | 2 | 67 | 3.416 | 0.689 | 99 |
| 31 | W 2- 2 | 30 X 30 | 30.0 | R | 5 | 2 | 68 | 4.041 | 0.420 | 99 |
| 32 | W14- 3 | 41 X 34 | 5.0 | L | 0 | 2 | 213 | 2.538 | 13.709 | 811 |
| 33 | W 1- 2L | 30 X 30 | 19.2 | R | 1 | 2 | 15 | 0.891 | 0.420 | 99 |
| 34 | W14- 3 | 41 X 34 | 5.0 | L | 0 | 2 | 215 | 2.562 | 13.709 | 811 |
| 38 | W13- 2 | 48 X 60 | 8.0 | R | 0 | 4 | 15 | 0.704 | 3.646 | 403 |
| 40 | W 2- 2 | 30 X 30 | 30.0 | R | 5 | 2 | 45 | 2.674 | 0.420 | 99 |
| 45 | W13- 2 | 48 X 60 | 8.0 | R | 0 | 4 | 17 | 0.612 | 13.210 | 532 |
| 47 | W 2- 1 | 30 X 30 | 40.0 | R | 5 | 2 | 54 | 2.964 | 0.689 | 99 |
| 52 | W 1- 2R | 48 X 48 | 19.2 | L | 1 | 2 | 31 | 1.465 | 1.131 | 99 |
| 54 | W 9- 2 | 48 X 48 | 6.0 | L | 0 | 2 | 34 | 1.583 | 13.709 | 231 |
| 60 | W 9- 2 | 48 X 48 | 6.0 | L | 0 | 2 | 75 | 3.491 | 13.709 | 231 |
| 62 | W13- 2 | 48 X 60 | 8.0 | R | 0 | 4 | 83 | 2.988 | 13.210 | 532 |

------NUMBER OF RECORDS PRINTED = ------

Note: 1 in = 2.54 cm; 1 ft = 0.305 m.

subjects included a sales representative of a sheeting manufacturer, and two people involved in highway research. One of the township managers had to be dropped because the headlights of the research vehicle were found to be mis-aimed after his data were obtained.

## 5. Equipment

The primary data collection tool was a 1976 Ford E250 window van equipped with calibrated halogen headlamps and a digital measuring instrument (DMI). Photometric grid values at 12.8 volts were obtained for the headlamps prior to installation. To ensure that operating voltage would be uniform at 12.8 volts throughout data collection, an auxiliary 6-volt battery and voltage regulator were installed in the headlamp circuit. The DMI provides a dash-mounted, switch-operated, digital distance display. Input data for the DMI comes from an electro-mechanical sensor installed at the transmission-speedometer cable union, affording accuracy to ±3 ft/1,000 ft (± 0.9 m/305 m).

Auxiliary equipment included a standard cassette tape recorder with built-in condenser microphone and a supply of blank tapes.

## 6. Results

The primary results of the field evaluation are the comparisons of the sign management system and test subjects with respect to sign replacement decisions. As pointed out previously, the lack of research data on available luminance made it necessary to use SIA as the criterion of interest. A number of different sign replacement comparisons were made, each of which compared the subject judgments with different replacement criteria programmed into the sign management model. The sign management model is capable of using a number of different replacement strategies including different SIA values, different sign types, and different sign criticality levels as criteria for replacement. For illustrative purposes a number of these replacement strategies will be discussed as they relate to replacements judged necessary by the test subjects. Table 6 shows a sample of the types of strategies that could be used. The simplest strategy is one which uses only SIA as a criterion. These would be represented by strategies 1, 2, and 3 on table 6. Strategy 1 uses the SIA values suggested by Sivak and Olson (1985), which were derived for signs with legends.[1] Strategies 2 and 3 represent a 75 percent and 50 percent reduction of these recommended values, respectively. Strategy 4 represents the use of both SIA and sign criticality as criteria for replacement. For this strategy the Sivak and Olson values are used for the more critical signs, i.e., those with a criticality rating equal to or less than 2, and 50 percent of the Sivak and Olson values are used for the less critical signs, i.e., those with a criticality rating of greater than 2. Strategy 5 uses both SIA and sign type as criteria. Here the Sivak and Olson recommendations are used for the alpha-numeric signs, and 50 percent of the

[1] The minimum SIA values recommended by Sivak and Olson are: Right-mounted = 24; left-mounted = 90; median-mounted = 24; overhead = 114 (see reference 9).

Table 6. Sign replacement criteria for illustrative strategies.

| REPLACEMENT STRATEGY | SIA BY LOCATION | | | | CRITICALITY | | TYPE | |
|---|---|---|---|---|---|---|---|---|
| | R | L | M | OH | ≤ 2 | > 2 | SYMBOL | ALPHA |
| # 1 | 24 | 90 | 24 | 114 | - | - | - | - |
| # 2 | 18 | 68 | 18 | 84 | - | - | - | - |
| # 3 | 12 | 45 | 12 | 57 | - | - | - | - |
| # 4 | 24 | 90 | 24 | 114 | X | | - | - |
| | 12 | 45 | 12 | 57 | | X | - | - |
| # 5 | 24 | 90 | 24 | 114 | - | - | - | X |
| | 12 | 45 | 12 | 57 | - | - | X | - |
| # 6 | 24 | 90 | 24 | 114 | X | - | - | X |
| | 12 | 45 | 12 | 57 | - | X | - | X |
| | 12 | 45 | 12 | 57 | X | - | X | - |
| | 6 | 23 | 6 | 29 | - | X | X | - |

recommended values are used for the symbol signs. The underlying rationale for a strategy such as this is that the alpha-numeric signs have shorter legibility distances, and therefore must be brighter to afford legibility distance equivalent to the recognition distance afforded by less bright symbol signs. That is, symbols afford greater recognition distance than letters on signs of equivalent size (Jacobs et al., 1975).[11] Strategy 6 considers SIA, criticality, and sign type as criteria for replacement. Here the Sivak and Olson values are used for critical alpha-numeric signs; 50 percent of these values are used for less critical alpha-numeric signs and for critical symbol signs; and 25 percent of the recommended values are used as criteria for the less critical symbol signs.

The different strategies, of course, result in differing numbers of signs being indicated for replacement by the model. The number of replacements generated by the model can be used as a basis of comparison with the signs indicated for replacement by the test subjects. It will be recalled that eight expert subjects were used to obtain the replacement judgments. In order to use a single value against which to compare the output of the model with the subject judgments, it was necessary to use the median judgment from the subject group. However for some signs in the inventory, there was a great deal of disagreement. Table 7 shows the signs for which more than two of the eight subjects disagreed with the majority decision. The decisions made by subjects regarding replacement reflected their judgment of the criticality of each sign and this may not be the same criticality rating given the sign by the research staff. This could result in differences between the model and the subject judgments. Also, the model decisions are made on the basis of SIA, whereas the subjects were making judgments on the basis of available luminance.

The first comparison to be discussed used the SIA criterion replacement values recommended by Sivak and Olson (1985).[9] Variations thereof were used for additional comparisons. These SIA values were used as the criterion values in the sign management model and run with the sign inventory used for the field data collection (as shown in table 5). Tables 8 (warning), 9 (regulatory), and 10 (other) show the signs replaced by test subjects as compared

Table 7. Signs exhibiting replacement decision disagreement among subjects.

| ID | CODE LEGEND | LOC | SIA |
|---|---|---|---|
| 24 | W 2 - 2 | R | 8 |
| 54 | W 9 - 2 | L | 34 |
| 60 | W 9 - 2 | L | 75 |
| 03 | R 2 - 1 | R | 1 |
| 05 | R 2 - 1 | R | 1 |
| 11 | R 4 - 1 | R | 1 |
| 14 | R 1 - 1 | R | 29 |
| 29 | R 1 - 1 | R | 58 |
| 39 | R 1 - 1 | R | 57 |
| 43 | R 5 - 1 | L | 169 |
| 44 | R 5 - 1 | L | 82 |
| 46 | R 4 - 7 | L | 24 |
| 48 | R 1 - 1 | R | 52 |
| 49 | R 4 - 9 | L | 83 |
| 64 | R 3 - 5 | O | 22 |
| 36 | M 1 - 4 | R | 49 |
| 42 | M 1 - 4 | R | 21 |
| 55 | M 1 - 4 | R | 68 |
| 23 | D 2 - 2 | R | 68 |

to each of the sample model strategies used. As indicated in table 8, which includes the warning signs, there was excellent agreement between the test subject decisions and the model strategies. For the regulatory and other signs shown in tables 9 and 10, the agreement was not as good, particularly with strategy 1, which used the Sivak and Olson minimum SIA values. This implies that, at least for regulatory signs, experts making judgments in a field driving situation do not agree with the minimum brightness requirement established by Sivak and Olson. However, if the comparison is reviewed more closely it can be shown that this is not necessarily the case. Since strategy 1 shows the greatest disparity between subject judgments and the output of the model, this comparison will be reviewed in some detail to illustrate that the apparent disparity may not be as great as it appears.

Using strategy 1 the model indicated that 26 of the 66 signs did not meet the minimum SIA specified and would therefore be listed for replacement. The test subjects judged that 18 of the signs should be replaced. The model and the subjects were in agreement as to replacement of 17 of the 66 signs.

Table 8. Comparison of signs replaced using different criteria (warning signs).

| | | | | SUBJECT REPLACE-MENTS | MODEL REPLACEMENT STRATEGIES | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | CODE | LOC | SIA | | #1 | #2 | #3 | #4 | #5 | #6 |
| 02 | W14-5 | R | 67 | | | | | | | |
| 04 | W14-5 | R | 5 | x | x | x | x | x | x | x |
| 06 | W15-2 | R | 82 | | | | | | | |
| 07 | W 1-2 | R | 50 | | | | | | | |
| 08 | W 1-1 | R | 1 | x | x | x | x | x | x | x |
| 10 | W15-2 | R | 81 | | | | | | | |
| 13 | W 1-1 | R | 24 | | | | | | | |
| 16 | W 2-1 | R | 8 | x | x | x | x | x | x | x |
| 18 | W 2-4 | R | 27 | | | | | | | |
| 20 | W 2-4 | R | 1 | x | x | x | x | x | x | x |
| 21 | W 2-1 | R | 46 | | | | | | | |
| 22 | W15-2 | R | 1 | x | x | x | x | x | x | x |
| 24 | W 2-2 | R | 8 | x | x | x | x | x | x | x |
| 25 | W15-2 | R | 30 | | | | | | | |
| 27 | W 1-4 | R | 67 | | | | | | | |
| 31 | W 2-2 | R | 68 | | | | | | | |
| 32 | W14-3 | L | 213 | | | | | | | |
| 33 | W 1-2 | R | 15 | x | x | x | | x | | |
| 34 | W14-3 | L | 215 | | | | | | | |
| 38 | W13-2 | R | 15 | x | x | x | | | x | |
| 40 | W 2-1 | R | 45 | | | | | | | |
| 45 | W13-2 | R | 17 | x | x | x | | | x | |
| 47 | W 2-1 | R | 54 | | | | | | | |
| 52 | W 1-2 | R | 31 | | | | | | | |
| 54 | W 9-2 | L | 34 | | x | x | x | x | x | x |
| 60 | W 9-2 | L | 75 | | | | | | | |
| 62 | W13-2 | R | 83 | | | | | | | |
| Number of Signs Replaced | | | | 9 | 10 | 10 | 7 | 8 | 9 | 7 |

Table 9. Comparison of signs replaced using different criteria (regulatory signs).

| ID | CODE | LOC | SIA | SUBJECT REPLACE-MENTS | MODEL REPLACEMENT STRATEGIES #1 | #2 | #3 | #4 | #5 | #6 |
|---|---|---|---|---|---|---|---|---|---|---|
| 03 | R 2-1 | R | 1 | x | x | x | x | x | x | x |
| 05 | R 2-1 | R | 1 | x | x | x | x | x | x | x |
| 11 | R 4-1 | R | 1 | | x | x | x | x | x | x |
| 12 | R 2-1 | R | 89 | | | | | | | |
| 14 | R 1-1 | R | 29 | | | | | | | |
| 15 | R 2-1 | R | 139 | | | | | | | |
| 19 | R 2-1 | R | 112 | | | | | | | |
| 26 | R 1-1 | R | 78 | | | | | | | |
| 28 | R 2-1 | R | 136 | | | | | | | |
| 29 | R 1-1 | R | 58 | | | | | | | |
| 30 | R 4-1 | R | 88 | | | | | | | |
| 39 | R 1-1 | R | 57 | | | | | | | |
| 41 | R 5-1 | L | 33 | x | x | x | x | x | x | x |
| 43 | R 5-1 | L | 169 | | | | | | | |
| 44 | R 5-1 | L | 82 | | x | | | x | | |
| 46 | R 4-7 | M | 24 | | x | x | x | x | x | x |
| 48 | R 1-1 | R | 52 | | | | | | | |
| 49 | R 4-9 | L | 83 | x | x | | | | | |
| 50 | R 4-7 | M | 60 | | | | | | | |
| 51 | R 4-9 | L | 24 | x | x | x | x | x | x | |
| 56 | R 4-7 | M | 106 | | | | | | | |
| 57 | R 4-9 | L | 68 | x | x | | | | | |
| 58 | R 3-6 | O | 25 | x | x | x | x | x | x | x |
| 59 | R 4-7 | M | 69 | | | | | | | |
| 61 | R 3-5 | O | 84 | | x | | | x | | |
| 63 | R 3-9 | O | 82 | | x | x | | x | | |
| 64 | R 3-5 | O | 22 | | x | x | x | x | x | x |
| 65 | R 4-7 | M | 100 | | | | | | | |
| 66 | R 3-6 | O | 46 | | x | x | x | x | x | x |
| Number of Signs Replaced | | | | 7 | 14 | 10 | 9 | 12 | 9 | 8 |

Table 10. Comparison of signs replaced using different criteria (other signs).

| ID | CODE | LOC | SIA | SUBJECT REPLACE-MENTS | MODEL REPLACEMENT STRATEGIES #1 | #2 | #3 | #4 | #5 | #6 |
|---|---|---|---|---|---|---|---|---|---|---|
| 35 | M 1-4 | R | 30 | | | | | | | |
| 36 | M 1-4 | R | 49 | | | | | | | |
| 42 | M 1-4 | R | 21 | | x | | | | x | |
| 55 | M 1-4 | R | 21 | x | x | | | | x | |
| 23 | D 2-2 | R | 68 | x | | | | | | |
| 37 | D 1-3 | R | 281 | | | | | | | |
| 53 | D 1-3 | R | 291 | | | | | | | |
| 09 | S 3-1 | R | 44 | | | | | | | |
| 17 | S 3-1 | R | 42 | | | | | | | |
| Number of Signs Replaced | | | | 2 | 2 | 0 | 0 | 0 | 2 | 0 |

The sign inventory used was made up primarily of 27 warning signs and 30 regulatory signs. Within these two groups the concordance between subjects and model was, as mentioned, much better for the warning signs. For this group there was total agreement with the exception of one sign which the model replaced and the subjects did not. This sign was a left-mounted, LANE ENDS MERGE LEFT sign with an SIA of 34. Further, for this sign there was great disagreement among the test subjects, with four judging that the sign should not be replaced and four judging the opposite. For the regulatory signs there were seven signs that were replaced by the system and not by subjects. However, of these seven signs, four elicited considerable disagreement among subjects. Considering all of the factors that might be influential in judging the need for replacement, the relationship between the model and the subject ratings using SIA as a criterion appears reasonable.

The cost associated with the replacements indicated by the model for the 66-sign inventory is $1,290. By comparison the cost associated with the signs replaced only by subjects is $1,164. If it can be assumed that the distribution of SIA values in the inventory used for the study is representative of a municipal inventory, the estimated costs for replacements for a 6,600-sign inventory would then be $129,000 (model) versus $116,400 (subject). This represents a difference of $12,600 for the most costly strategy used with the model. This was the strategy that was the most conservative with regard to minimum luminance. It will be noted that this is the only strategy for which estimated replacement cost based on the model decisions was greater than the costs associated with test subject decisions. Based on a 6,600-sign inventory, the costs of the other model strategies are as follows: Strategy 2 = $107,400; strategy 3 = $67,800; strategy 4 = $93,000; strategy 5 = $97,800; and strategy 6 = $64,200. If one considers the cost of having an individual visually check signs, the use of the model not only results in a cost saving in most cases, it results in new signs for those that may be of questionable effectiveness. Further, the use of the model to identify replacements will result in more uniform luminance values across jurisdictions in that the variation produced by human judgment is removed from the decision process.

## SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The results of the evaluation have demonstrated that sign replacement strategies based primarily on SIA and used with the sign management system produce sets of replaced signs that compare extremely well with those produced by expert subjects. As such, the system could provide a cost-effective tool for use by State or local agencies. However, application of the procedure requires that an agency have available a sign inventory which includes reflectometer (SIA) information. While some agencies now have sign inventories and more are likely in the near future, regular use of a reflectometer on signs in the field to obtain SIA readings is not nearly as likely. Further, the acquisition of reflectometer readings, as in the evaluation study, is as labor-intensive as the inspection approach to sign replacement decisions. The cost-effective use of the procedure described here depends on the acquisition of sign deterioration information. The information necessary to determine the relationship of sign and material age and location to sign brightness is not currently available. We therefore strongly recommended that a focused research effort be undertaken to acquire such information.

With regard to a determination of sign deterioration from aging, it is recognized that such a study would take a long time to obtain the data required. An initial study could be conducted in any State agencies that have a record system which indicates the type of material used in signs, the associated SIA, and the length of time the signs have been in service. The research would then consist of taking reflectometer readings of signs that have been in place for various periods of time in various types of locations. These measurements could then be compared with the original SIA to obtain a deterioration rate; this, of course, assumes that the agencies have taken initial readings of the materials used or that the specifications of the manufacturers are accurate for each batch of material.

A second research effort that would be desirable is one which would provide some field validation of the minimum SIA values recommended by Sivak and Olson (1985).(9) As judged from the current study, these values appear to be reasonable with respect to the signs that would be replaced by observers. However, it would seem that driver performance data should be the ultimate criterion by which such recommendations are judged. Such a field validation could be divided into several studies, with the separate studies being a function of sign location. For example, a verification of the values for right-mounted signs would accommodate most of the signs used on two-lane roadways and many of those used on multilane facilities. Overhead, median, and left-side signs could be handled in a separate study, in that these locations involve a lower proportion of the total sign population.

Research needed both for general purposes and to enhance the utility of the system includes a study of luminance requirements for conspicuity of regulatory signs, overhead guide signs, and STOP signs. Requirements should be established for levels of complexity as specified for warning signs in Mace et al. (1985).[7] These data should then be incorporated into the system.

Other research needed is a test of the sight distance model. Are the required legibility, recognition, and conspicuity distances predicted realistic in terms of providing an adequate margin of safety? Any research on luminance requirements for signs must make assumptions concerning where a sign must be noticed and recognized or read. Either this model must be validated, or one may accept overly conservative values for sign replacement. However, more than the model must be validated. The model may have sufficient accuracy but give poor results because of the input data, i.e., the data on decision complexity, message length, criticality, etc. Whether for the model or a table of values for specific signs, a means of estimating required distances would be useful to managers of sign inventories and researchers.

Also useful would be research focused on calibrating symbol signs for recognizability. The system developed in the current research assumed that symbol messages had twice the "legibility" of alpha-numeric legends on the same size blank. A study which determined recognition distances for the major symbol signs would be helpful.

Once data from studies such as those described above are available and it is possible to predict the SIA as a function of sign age and location, the existing sign management system can be used to determine which signs in an inventory should be replaced at any given time based on minimum SIA values. The use of such an aid in managing a sign inventory will result in greater uniformity in sign luminance and will be cost-effective in that, except for periodic quality control checks, it will preclude the need for labor-intensive field evaluations.

APPENDIX A: Analytical Determination of Minimum Brightness Standards for Sign Legibility

Research on the relationship of sign brightness and legibility has generally used one of three measures of brightness: Uniformity of sign background; level of internal contrast; and luminance of the legend or background, whichever is brighter.

1. Sign Background Uniformity

The first candidate measure of sign brightness is the uniformity of the sign background. If the sign face degrades unevenly as it ages, then the sign assumes a mottled appearance that impairs legibility. Three recommendations for sign luminance uniformity are presented in table 11.

Table 11. Recommendations for the maximum ratio of luminances across the sign background.

| SOURCE | RECOMMENDED MAXIMUM RATIO OF BACKGROUND LUMINANCES |
|---|---|
| ITE, 1960 | 5:1 |
| Allen et al., 1967 | 10:1 |
| Dahlstedt, 1974 | 6:1 |

The Institute of Traffic Engineers recommends a ratio of 5:1 as the maximum acceptable ratio of luminances for externally lighted traffic signs.(17) On the other hand, a controlled field study of internally illuminated signs concluded that variation in the luminance of different areas of the sign should be no more than 10:1 (Allen et al., 1967).(18) A study specifically designed to establish the relationship between the luminance uniformity of the 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 fL (3.15 to 12.62 cd/ft$^2$; 33.96 to 136.17 cd/m$^2$) (Dahlstedt, 1974).(19) 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. It might be noted that the luminance of type II and type III white sheeting (the brightest sheeting color) rarely exceeds 9.9 fL (3.15 cd/ft$^2$, 33.92 cd/m$^2$) under low-beam illumination (Youngblood and Woltman, 1971; King and Lunenfeld, 1971).[20,21] This observation implies that the luminance uniformity of the sign background is not closely related to the legibility of retroreflective highway signs constructed with types II and III sheeting. Moreover, casual observations by highway agency personnel of sign deterioration patterns indicate that degradation tends to be uniform, so that luminance disparities on the sign background are a very infrequent occurrence. For these reasons, while luminance uniformity may be relevant to the legibility of illuminated signs, it is not germane to retroreflective signs constructed with materials currently available.

### 2. Internal Contrast

The contrast between the luminance of the sign legend and the luminance of the sign background is a second candidate measure of sign brightness that can be related to legibility performance. One common index of internal contrast is the luminance ratio between the legend and background of the sign, with the greater of the two values used in the numerator of the expression. An early study of the legibility of black-on-white signs as a function of internal contrast indicated that luminance ratios of 3.3:1 or greater resulted in at least 90 percent of the maximum obtainable legibility distance (Smyth, 1947).[3]

A later study of internal contrast requirements for the legibility of signs with white legends on blue, red, and green backgrounds found that as the level of sign background luminance decreases, the luminance ratio required for legibility increases (Hills and Freeman, 1970).[22] These data suggest that in order to maintain 90 percent of the maximum obtainable legibility distance, the minimum acceptable luminance ratio ranges from 6:1 to 10:1, depending on the color of the sign background; the luminance ratios recommended by Hills and Freeman are presented in table 12.

Table 12. Minimum luminance ratios recommended by Hills and Freeman (1970).

| BACKGROUND COLOR | RECOMMENDED MINIMUM LUMINANCE RATIOS FOR 10% (MAXIMUM) REDUCTION IN LEGIBILITY | |
|---|---|---|
| | Legend Luminance 0.93 fL | Legend Luminance 2.92 fL |
| red | 8:1 | 10:1 |
| green | 7:1 | 7:1 |
| blue | 6:1 | 7:1 |

Note: 1 fL = 0.318 $cd/ft^2$ = 3.43 $cd/m^2$.

Somewhat lower luminance ratios were recommended by another team of investigators who examined the role of internal contrast in the legibility of signs with seven different color combinations. Luminance ratios of 2:1 or 3:1 were recommended to maintain "reasonable legibility" for all of the color combinations tested (Forbes et al., 1976; and Forbes, 1976).[23,24] In addition, increases in luminance ratio beyond 5:1 were found to have a negligible effect on further increases in legibility. The authors conclude that a luminance ratio anywhere from 3:1 to 7:1 is desirable for legibility. While the minimum acceptable luminance ratios that can be inferred from these data most closely approximate the findings of Smyth, the results of Forbes and his associates are in agreement with those of Hills and Freeman.

A study conducted by the New York State DOT examined subjective ratings of the legibility of existing signs along the highway as a function of luminance ratio and found an "apparent relationship" (Hahn et al., 1977).[25] These data suggest that for shoulder-mounted signs, if the acceptable subjective rating of sign legibility is "good," i.e., the sign can be read with slight difficulty and momentary observer uncertainty by familiar observers with unlimited viewing time, then the average minimum luminance ratio is approximately 3.85:1. Note that this value is not very different from those derived from the findings of both Smyth and Forbes.

The results of Hills and Freeman, and the Forbes team, indicate that legibility performance is asymptotic at some luminance ratio less than or equal to 10:1. That is, increases in luminance ratio beyond 10:1 do not result in notable improvements in legibility distance. This asymptote in performance enabled these researchers to recommend minimum standards for internal contrast. The findings of a more recent study, however, imply that maximum obtainable legibility performance is not asymptotic even to a luminance ratio of 100:1 (Olson and Bernstein, 1977).[8] Perhaps for this reason, these authors do not make any recommendations for minimum levels of internal contrast. On the other hand, their data are consistent with the Hills and Freeman finding that equivalent legibility distances require greater internal contrast as background luminance decreases.

A summary of recommended minimum luminance ratios derived from each of the studies is provided in table 13. While internal contrast has consistently been found to relate closely to legibility, this relationship applies only to signs with white letters on a colored background. For signs with a white legend on a black background and for signs with a black legend on a colored background, legibility is determined by the luminance of the brighter portion of the sign (Olson and Bernstein, 1977).[8] Consequently, a minimum brightness standard based solely on internal contrast would have little applicability to signs having either a black legend or a black background. More important, since most signs will not be in service until there is a complete loss of reflectivity, the internal contrast of a sign is essentially fixed for the duration of that sign's service life by the materials with which it is constructed (Woltman, 1983).[26] Of course, some variation in luminance ratio occurs as a result of dirt on the sign face and differential fading of colors caused by ultraviolet light, but changes due to these factors are temporary and minor, respectively. For these reasons, internal contrast is most relevant in sign design and construction. Internal contrast affects minimum brightness standards only to the extent that the level of brightness required to obtain a given legibility distance is determined by the sign's luminance ratio. The ratio is established by the materials with which the sign is constructed.

Table 13. Recommended minimum luminance ratios for internal contrast.

| SOURCE | RECOMMENDED MINIMUM LUMINANCE RATIO |
|---|---|
| Smyth, 1947 | 3.3:1 |
| Hills and Freeman, 1970 | 6:1 to 10:1 |
| Forbes et al., 1976 | 3:1 to 7:1 |
| Hahn et al., 1977 | 3.85:1 |
| Olson and Bernstein, 1977 | no recommendation |

3. Sign Luminance

a. Interactive Variables

The third possible index of sign brightness that can be related to legibility is sign luminance. Traditionally, when used in this context, sign luminance refers to the luminance of either the sign legend or the sign background, whichever is brighter; this definition will be used throughout this paper. Throughout the years, legibility as a function of sign luminance has been studied to a greater extent than any other measure of sign brightness. However, the relationship between these two factors has been shown to interact with several other variables, so simple comparisons of findings across studies are generally not possible. In fact, there is also no consensus across experiments about the effects of the interactions between selected variables (e.g., surround luminance) and sign luminance on legibility. A summary of the effects of these interacting variables on minimum luminance requirements is presented in figure 9.

The effects described in this figure are inferences based upon interpolations from the graphs and tables of results published in the references cited. Where possible, these interaction effects have been stated in terms of adjustments to minimum luminance requirements; in the remaining instances, effects have been described in terms of reductions in obtained legibility distances. An attempt was made to summarize observed effects in the simplest manner to provide a clear illustration of interactive patterns. Some precision was lost as a result. If, for example, two trend lines were

| INTERACTIVE VARIABLE<br>reference | OBSERVED EFFECT |
|---|---|
| **letter series/ratio of letter stroke width to height (SW/H)** | |
| Allen and Straub, 1955 (27) | Legibility distances of series A and C letters are about 50% and 70%, respectively, of series F letters. |
| Hills, 1972(28) | Legibility distances of series B, C, D, and E letters are about the same. |
| Hind et al., 1976(29) | Minimum Luminance Requirements for Legibility (MLRL) increase as SW/H decreases. |
| **direction of internal contrast** | |
| Smyth, 1947 | MLRL for black-on-white signs and white-on-black signs are about the same. |
| Allen and Straub, 1955 | For signs with luminances from 1 through 10 fL, MLRL are about 10 times greater for black-on-white signs than for white-on-black signs. |
| Allen et al., 1967 | For signs darker than 2 fL, MLRL are about 1.5 times greater for black-on-white signs than for white-on-black signs. |
| | For signs with luminances from 2 through 20 fL, MLRL are about 3.4 times greater for black-on-white signs than for white-on-black signs. |
| Hind et al., 1976 | For signs darker than 9.9 fL, MLRL are greater for black-on-white signs than for white-on-black signs. |
| | For signs brighter than 9.9 fL, MLRL vary as a function of the interaction between direction of internal contrast and SW/H. |

Figure 9. Interactive effects on minimum luminance requirements for legibility (MLRL).

| INTERACTIVE VARIABLE<br>reference | OBSERVED EFFECT |
|---|---|
| **level of internal contrast** | |
| Allen et al., 1967 | For signs darker than 2 fL, MLRL are about 1.7 times greater for signs with 75% internal contrast than for signs with 100% internal contrast.<br><br>For signs brighter than 2 fL, MLRL are at least 2 times greater for signs with 75% internal contrast than for signs with 100% internal contrast. |
| Hills and Freeman, 1970 | MLRL increase as level of internal contrast decreases. |
| Forbes et al., 1976 | MLRL increase as level of internal contrast decreases. |
| Olson and Bernstein, 1977 | MLRL increase as level of internal contrast decreases for signs with a white legend on a colored background. |
| **sign background color** | |
| Forbes et al., 1976 | MLRL increase from: black-on-white, black-on-yellow, white-on-blue, white-on-green, to white-on-grey. |
| Olson and Bernstein, 1977 | MLRL increase from: white-on-blue, white-on-green, to white-on-red.<br><br>MLRL increase from: black-on-white, black-on-orange, to black-on-yellow. |
| Olson et al., 1979(30) | MLRL increase from white-on-blue to white-on-green. |
| **level of surround luminance** | |
| Smyth, 1947 | MLRL are about 3 times greater for moderate surrounds (1 fL) than for very dark surrounds (0.001 fL). |

Figure 9. Interactive effects on minimum luminance requirements for legibility (MLRL) (continued).

| INTERACTIVE VARIABLE reference | OBSERVED EFFECT |
|---|---|
| **level of surround luminance (continued)** | |
| Forbes et al., 1976 | MLRL decrease as surround luminance increases, under laboratory conditions. |
| | MLRL for different surround luminances are about the same, under controlled field conditions. |
| Olson and Bernstein, 1977 | MLRL decrease as surround luminance increases. |
| Van Norren, 1981 | MLRL increase as surround luminance increases. |
| **level of ambient illumination** | |
| Allen and Straub, 1955 | For signs darker than 1 fL, MLRL are about 1.4 times greater for moderate ambient conditions (0.1 fc) than for very dark conditions (0.001 fc). |
| Elstad et al., 1962 | For signs brighter than 1 fL, MLRL are slightly greater for very dark ambient conditions (0.001 fc) than for moderate ambient conditions (0.1 fc). |
| | Legibility distances for moderate ambient conditions (illuminated suburban) and very dark conditions (no light sources other than headlamps) are about the same. |
| Allen et al., 1967 | For signs darker than 12 fL, MLRL are greater for very bright ambient conditions (3 fc) than for very dark conditions (0.01 fc). |
| | For signs brighter than 12 ftL, MLRL are greater for very dark ambient conditions (0.01 fc) than for very bright conditions (3 fc). |

Figure 9. Interactive effects on minimum luminance requirements for legibility (MLRL) (continued).

| INTERACTIVE VARIABLE<br>reference | OBSERVED EFFECT |
|---|---|
| **glare** | |
| Smyth, 1947 | MLRL are not affected by bright glare sources adjacent to the sign, unless the observer first fixates the glare source. |
| Allen et al., 1967 | For signs darker than 0.2 fL located in dark ambient conditions (0.01 fc), MLRL are about 3 times greater under conditions of opposing headlamp glare than for the no-glare condition. |
| | For signs brighter than 2 fL located in dark ambient conditions and for any sign located in brighter ambient conditions ($\geq$ 0.2 fc), MLRL for glare and no-glare conditions are about the same. |
| Olson et al., 1979 | MLRL increase only when the glare source is immediately adjacent to the sign and greater than or equal to 5,000 fL. |
| Sivak and Olson, 1982 (31) | MLRL increase only when the separation angle is not greater than 0.2°. |
| **observer age** | |
| Allen et al., 1967 | For signs darker than 10 fL, MLRL are about 1.6 times greater for observers older than 58 than for younger observers. |
| | For signs brighter than 10 fL, MLRL for young and old observers are about the same. |
| Olson and Bernstein, 1977 | Legibility distances obtained from observers older than 65 are about 67% of those obtained from young observers. |
| Olson et al., 1979 | Legibility distances obtained from observers older than 65 are about 75% of those obtained from observers ages 18-22. |
| Sivak et al., 1981(32) | Legibility distances obtained from observers ages 62-74 are about 65-77% of those obtained from observers younger than 25, even when age groups are matched on high luminance visual acuity. |

Figure 9. Interactive effects on minimum luminance requirements for legibility (MLRL) (continued).

| INTERACTIVE VARIABLE reference | OBSERVED EFFECT |
|---|---|
| **observer age (continued)** | |
| Sivak and Olson, 1982 | Legibility distances obtained from observers ages 65-75 and observers 20-30 are about the same, allegedly because age groups were matched on low luminance/high contrast visual acuity. |
| **viewing time** | |
| Forbes, 1976 | Legibility distances are about 1.5 times greater for extended viewing time (ordinary legibility) than for glance legibility, with a ceiling of about 60 ft/in (7.3 m/cm) for ordinary legibility. |
| Van Norren, 1981[33] | Legibility distances are about 1.5 times greater for unlimited viewing time than for a viewing time of 0.2 sec. |

Figure 9. Interactive effects on minimum luminance requirements for legibility (MLRL) (continued).

Note: 1 fL = 0.318 cd/ft$^2$ = 3.43 cd/m$^2$; 1 fc = 1 lumen/f$^2$ = 10.76 lumen/m$^2$.

not quite parallel, several measures of the difference between the two curves were made, and the average of these readings was used to estimate the magnitude of the difference. In cases where trend lines were markedly non-parallel, the order of the difference was described without any estimate of the magnitude of the effect. For these reasons, any estimate of the magnitude of the effect of a given variable should be regarded as an approximation. If more detail is required for a particular application of the data, the reference should be consulted.

The following conclusions about minimum luminance requirements for legibility (MLRL) can be derived from an examination of the effects described in figure 9:

- MLRL increase as the ratio of letter stroke width to letter height (SW/H) decreases.

- MLRL are greater for black-on-white signs than for white-on-black signs.

- MLRL increase as level of internal contrast decreases for signs with a white legend on a colored background.

- MLRL increase from white-on-blue, through white-on-green, to white-on-red.

- MLRL increase from black-on-white, through black-on-orange, to black-on-yellow.

- The data are inconsistent with regard to the interactive effect of sign luminance and surround luminance/ambient illumination on MLRL.

- MLRL are not influenced by glare, unless the glare source is very bright and immediately adjacent to the sign.

- MLRL increase with observer age, probably because of degraded low luminance/high contrast visual acuity among older people.

- Legibility distances are about 1.4 times greater for ordinary legibility (extended viewing time) than for glance legibility.

b. Derivation of Minimum Luminance Standards

The preceding inferences can be used to structure the parameters of a table of MLRL. However, one of the inferences indicates inconsistent findings regarding the effect of surround luminance/ambient illumination on luminance requirements for legibility. As a result, specifying separate requirements for different surround/ambient levels is not yet justified. Additional research is required to establish the effect of these two variables on MLRL.

On the other hand, there is consistent evidence among the observations in figure 9 that MLRL increase in situations where bright glare sources are located immediately adjacent to a sign and in situations where high workload--which does not allow drivers extended viewing time--creates conditions requiring glance legibility. Since the effects of these two variables are situation-specific, MLRL will be developed for the no-glare, extended-viewing-time condition only. These standards can then be adjusted by multipliers as required by the characteristics of driving situations. Since the magnitude of these multipliers cannot be determined from available data, their specification also awaits further research.

There is also strong support in figure 9 for the observation that MLRL increase with observer age. Because of this relationship, comparisons of results across studies must take subject sample differences into consideration. For the same reason, MLRL must also be tailored to a design observer. Since the majority of the research efforts relating luminance to legibility have used young people with normal visual acuity as subjects, MLRL will be designed for the young driver with normal acuity. This definition of the design observer for MLRL is not conservative in that drivers whose legibility performance is degraded by either age or poor acuity are required to recognize and compensate for their performance deficit.

The conclusions derived from figure 9 indicate that since the MLRL vary as a function of several different sign variables, a single luminance standard cannot be applied to all signs. That is, the particular MLRL applicable to a given sign depends on the letter series, the direction and level of internal contrast, and the color combination characteristic of that sign. These factors are all fixed by sign design guidelines at the time of construction and cannot be manipulated thereafter. Because of this, many of the trends have much relevance to sign design: for example, the lowest MLRL can be obtained with a white-on-black sign with maximum SW/H and internal contrast. However, since the overall amount of light returned to the observer by such a sign would be low due to the dark sign background, any gain in legibility would be obtained at the expense of detectability and conspicuity. Moreover, if a new sign of this type were situated in a very dark surround, legibility probably would also be degraded by the effects of irradiation.

Ideally, then, a table of minimum luminance standards for official highway signs should include luminance requirements for each sign color combination with each letter series currently used. In addition, MLRL within each cell of such a table also would vary for different levels of internal contrast, which is determined by the materials and procedure used to differentiate the legend from the sign background. Unfortunately, completing this ideal table of standards can only be partially accomplished with the data presently available. Nevertheless, the envisioned table will be used as a model for developing luminance requirements even though many of the cells in the table must now remain empty.

The formidable task of specifying the entire family of minimum luminance standards can be reduced by controlling level of internal contrast. Since internal contrast affects only the legibility of signs with a white legend on a colored background, its effect on the legibility of signs with either a black legend or background can be ignored (Olson and Bernstein, 1977).(8) Also, rather than develop requirements for all possible levels of internal contrast, the MLRL might be specified only for the most frequently occurring luminance ratio characteristic of a given color combination. The most practical means of determining this ratio is to use the acceptance standards for retroreflective sheeting specified in "FP-79."(34). These standards are expressed in units of specific intensity per unit area (SIA), a measure of sign reflectivity. With a fixed source of illumination and a fixed viewing geometry, the ratio of real-world luminances obtained with two sheeting colors is equal to the ratio of SIA for those same two colors. As a result, assuming that all sheeting colors exceed SIA standards to a similar degree, the ratio of SIA acceptance standards for any two sheeting colors can be used as a rough index of the luminance ratio for a sign comprised of those two colors. Since legends made of type II and type III sheeting are most frequently used with type II and type III backgrounds, respectively (Olson and Bernstein, 1977), the modal luminance ratio for a sign of particular color combination is equal to the ratio of SIA acceptance standards for those two colors within each sheeting type.(8) These SIA acceptance standards and the modal luminance ratios are presented in tables 14 and 15, respectively. The bottom row of table 15 lists the luminance ratios selected to represent the color combinations of interest. Since MLRL increase as internal contrast decreases, each chosen value is generally the most conservative (i.e., smallest) luminance ratio characteristic of a given color combination across the four viewing conditions delineated in the tables. These are the ratios, then, that will be assumed in developing MLRL for signs with the relevant color combinations.

Table 14. Acceptance standards for specific intensity per unit area (SIA) specified in "FP-79."

| Observation Angle (°) | Entrance Angle (°) | MINIMUM SPECIFICATIONS FOR SPECIFIC INTENSITY PER UNIT AREA (SIA) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | White | | Red | | Green | | Blue | |
| | | Type II Sheeting | Type III Sheeting | Type II Sheeting | Type III Sheeting | Type II Sheeting | Type III Sheeting | Type II Sheeting | Type III Sheeting |
| 0.2 | - 4 | 70 | 250 | 14.5 | 45 | 9.0 | 45 | 4.0 | 20.0 |
| 0.2 | + 30 | 30 | 150 | 6.0 | 25 | 3.5 | 25 | 1.7 | 11.0 |
| 0.5 | - 4 | 30 | 95 | 7.5 | 15 | 4.5 | 15 | 2.0 | 7.5 |
| 0.5 | + 30 | 15 | 65 | 3.0 | 10 | 2.2 | 10 | 0.8 | 5.0 |



Table 15. Luminance ratios for sign legends and backgrounds with the same type of sheeting.

| Observation Angle (°) | Entrance Angle (°) | LUMINANCE RATIOS | | | | | |
|---|---|---|---|---|---|---|---|
| | | White-on-Red | | White-on-Green | | White-on-Blue | |
| | | Type II Sheeting | Type III Sheeting | Type II Sheeting | Type III Sheeting | Type II Sheeting | Type III Sheeting |
| 0.2 | - 4 | 4.82 | 5.56 | 7.77 | 5.56 | 17.50 | 12.50 |
| 0.2 | + 30 | 5.00 | 6.00 | 8.57 | 6.00 | 17.64 | 13.64 |
| 0.5 | - 4 | 4.00 | 6.33 | 6.67 | 6.33 | 15.00 | 12.67 |
| 0.5 | + 30 | 5.00 | 6.50 | 6.82 | 6.50 | 18.75 | 13.00 |
| Selected Luminance Ratios: | | 4:1 | | 6:1 | | 12:1 | |

Because of all of the variables that interact with luminance to determine legibility performance, any attempt to analytically derive MLRL by abstracting data from several different studies requires consideration of the experimental conditions within each of the studies. The parameters relevant to studies of legibility as a function of luminance include the characteristics of the sign, subjects, viewing conditions, and the dependent measure. A summary of the studies that relate luminance and legibility in terms of these parameters is presented in table 16. Because of the differences among the studies described in this table, direct comparisons of results concerning luminance requirements for legibility are often not possible. However, despite the variations in empirical conditions, these studies provide essentially all of the information currently available for describing sign legibility as a function of sign luminance.

As noted previously, the relationship between legibility and luminance depends on both the letter series (SW/H) of the legend and the color combinations of the sign. For this reason, the analysis of the studies listed in table 16 was designed to identify luminance requirements for each letter series within each color combination; surround conditions were also included in the analysis and are defined in table 17. The data that were reviewed in order to derive these luminance requirements are summarized in table 18. These data were obtained via interpolations from the graphs and tables published in the references cited. Unfortunately, this procedure has undoubtedly introduced some degree of additional error into the data; however, without the original data, this error was unavoidable.

One of the most obvious features of table 18 is the inconsistency of the data within a given condition across studies. To illustrate, the luminance required to achieve 50 ft/in (6 m/cm) legibility for a black-on-white sign with a legend SW/H equal to 0.2 ranges from 0.027 to 10 fL (0.009 to 3.18 $cd/ft^2$; 0.092 to 34.3 $cd/m^2$). These data are somewhat more interpretable, however, when considered in the context of the conditions under which the studies were conducted. Many of the more relevant conditions have been described in table 16. A more detailed analysis of the original references

Table 16. Comparison of experimental conditions of studies relating luminance and legibility.

| SOURCE | SIGN | SUBJECTS | | VIEWING CONDITIONS | | DEPENDENT MEASURE |
|---|---|---|---|---|---|---|
| | Legend | Age Range | Acuity Range | Reading Time | Testing Situation | Criterion |
| Smyth, 1947 | NO THROUGH ROAD | ----- | ----- | not restricted | static lab | read legend |
| Allen and Straub, 1955 | three-letter syllables | 20-35 | 20/25-20/17 | 1 second | static lab | read legend |
| Allen, 1958 (35) | guide sign messages | 17-63 | 20/25-20/15 | not restricted during 15-mi/h approach | dynamic field | read legend |
| Allen, et al., 1967 | three-letter words | 18-81 | ----- | not restricted during 15-mi/h approach | dynamic field | read legend |
| Hills and Freemen, 1970 | one or four letters: CDGO | 21-28 | 6/6-6/5 | not restricted | static lab | identify letter with ease |
| Forbes et al., 1976 [lab] | O or Landolt C | college | ----- | not restricted | static lab | identify O or gap orientation |
| Forbes et al., 1976 [field] | square letter E | adult | ----- | not restricted during slow approach | dynamic field | identify letter orientation |
| Hind et al., 1976 | One-digit numeral | 18-24 | 6/21-6/3.3 | 2.5 seconds | static lab | identify numeral |
| Richardson, 1976 (36) | pattern of vertical bars | young adult | 20/25-20/15 | not restricted | static field | report resolvable pattern |
| Olson and Bernstein, 1977 | Landolt C | 20-32 | 20/20 or better | 1 second | static lab | identify gap orientation |
| Van Norren, 1981 | Landolt C | 20-35 | 2.5-1.5 | not restricted | static lab | identify gap orientation |

suggests additional explanations for the discrepancies among the data. For example, the luminance requirements, including the 10 fL (3.18 cd/ft$^2$; 34.3 cd/m$^2$) requirement cited above for 50 ft/in (6 m/cm) legibility, determined by the laboratory study of Forbes et al. (1976) are inordinately high relative to the results of comparable studies.[23] One explanation for the Forbes data concerns the stimuli used in the study. These stimuli were projections of colored slides. Unfortunately, colored slides do not faithfully reproduce signs. These stimuli were probably characterized by poor resolution and different levels of color saturation compared to views of real signs. Considering this, the high luminance requirements found by the Forbes study are more understandable. Similar inconsistencies among the data can be explained to some extent by such factors as subject age and visual acuity, dynamic versus static viewing conditions, and the specific nature of the legibility task required for successful performance.

Table 17. Definition of surround conditions.

| SURROUND CONDITION | DESCRIPTION | fL | fc[1] |
|---|---|---|---|
| Very Dark | no light sources other than the sign and headlamps | $\leq$0.037 | $\leq$0.0049 |
| Dark | occasional luminaires and advertising signs | 0.038-0.488 | 0.005-0.049 |
| Moderate | intermittent luminaires and/or advertising signs | 0.449-1.751 | 0.05-0.49 |
| Bright | continuous luminaires and/or frequent advertising signs | 1.752-4.44 | 0.5-2.99 |
| Very Bright | very high density of luminaires and/or advertising signs | $\geq$4.45 | $\geq$ 3 |

[1]Refers to average footcandles in the vertical plane along a longitudinal section of the road.

Note: 1 fL = 0.318 cd/ft$^2$ = 3.43 cd/m$^2$; 1 fc = 1 lumen/ft$^2$ = 10.76 lumen/m$^2$.

Table 18. Legibility performance as a function of sign luminance (fL): black on white.

| LETTER SERIES (SW/H) | SOURCE | 20 ft/in | | 30 ft/in | | 40 ft/in | | 50 ft/in | | 60 ft/in | | 70 ft/in | | 80 ft/in | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile |
| **VERY DARK SURROUND** | | | | | | | | | | | | | | | |
| A (.11) | Allen & Straub (1955) | | | 0.24 | | 5.3 | | | | | | | | | |
| - (.125) | Hind et al. (1976) | | | | | | | 1.05 | | | | | | | |
| C (.143) | Allen & Straub (1955) | | | | | 0.23 | | 0.87 | | | | | | | |
| - (.167) | Hind et al. (1976) | | | | | | | 0.75 | | | | | | | |
| F (.187) | Allen & Straub (1955) | | | | | | | 0.11 | | 0.34 | | 1.4 | | 13.0 | |
| - (-) | Smyth (1947) | | | | | | | | 1.0 | | | | | | |
| **DARK SURROUND** | | | | | | | | | | | | | | | |
| E (.172) | Allen et al. (1967) | | | | | 0.78 | | 7.6 | | | | | | | |
| - (.2) | Van Norren (1981) | 0.04 | | 0.08 | | 0.19 | | 0.76 | | 1.90 | | 7.59 | | 38.0 | |
| **MODERATE SURROUND** | | | | | | | | | | | | | | | |
| A (.11) | Allen & Straub (1955) | | | 0.30 | | 5.3 | | | | | | | | | |
| C (.143) | Allen & Straub (1955) | | | | | 0.30 | | 0.94 | | 64.0 | | | | | |
| E (.172) | Allen et al. (1967) | 0.27 | | 0.77 | | 2.4 | | 15.6 | | | | | | | |
| F (.187) | Allen & Straub (1955) | | | | | | | 0.17 | | 0.46 | | 1.5 | | 10.0 | |
| - (.2) | Forbes et al. (1976) lab[1] | | | 2.3 | | 10.0 | | 45.0 | | | | | | | |
| - (.2) | Olson & Bernstein (1977)[1] | | | | | | 0.027 | | 0.084 | | 0.44 | | 1.5 | | |
| - (.2) | Van Norren (1981) | 0.06 | | 0.13 | | 0.32 | | 1.28 | | 3.21 | | 12.9 | | 64.2 | |
| **BRIGHT SURROUND** | | | | | | | | | | | | | | | |
| - (-) | Smyth (1947) | | | | | | | | 3.5 | | | | | | |
| **VERY BRIGHT SURROUND** | | | | | | | | | | | | | | | |
| E (.172) | Allen et al. (1967) | 0.41 | | 0.91 | | 2.0 | | 6.6 | | 34.2 | | | | | |
| - (.2) | Van Norren (1981) | 0.23 | | 0.46 | | 1.16 | | 4.64 | | 11.6 | | 46.4 | | 232.0 | |

[1]Range of surround conditions collapsed.

Table 18. Legibility performance as a function of sign luminance (fL) (continued): black on orange.

| LETTER SERIES (SW/H) | SOURCE | 20 ft/in | | 30 ft/in | | 40 ft/in | | 50 ft/in | | 60 ft/in | | 70 ft/in | | 80 ft/in | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile |
| **MODERATE SURROUND** | | | | | | | | | | | | | | | |
| - (.2) | Olson & Bernstein (1977)[1] | | | | | | 0.08 | | 0.24 | | 0.9 | | 2.2 | | |

[1]Range of surround conditions collapsed.



black on yellow.

| LETTER SERIES (SW/H) | SOURCE | 20 ft/in | | 30 ft/in | | 40 ft/in | | 50 ft/in | | 60 ft/in | | 70 ft/in | | 80 ft/in | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile |
| **MODERATE SURROUND** | | | | | | | | | | | | | | | |
| - (.2) | Forbes et al. (1976)lab[1] | | | 2.8 | | 16.0 | | | | | | | | | |
| - (.2) | Forbes et al.(1976)field[1] | | | | | | 0.43 | 0.60® | 1.3 | | | | | | |
| - (.2) | Olson & Bernstein (1977)[1] | | | | | | 0.10 | | 0.38 | | 1.4 | | 2.2 | | |

[1]Range of surround conditions collapsed.
®Curve drops below 40 ft/in performance level and then rises above it again at 0.74 fL.

Table 18. Legibility performance as a function of sign luminance (fL) (continued): white on black.

| LETTER SERIES (SW/H) | SOURCE | 20 ft/in | | 30 ft/in | | 40 ft/in | | 50 ft/in | | 60 ft/in | | 70 ft/in | | 80 ft/in | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\overline{X}$, mdn, best fit line | ≥ 85 %ile | $\overline{X}$, mdn, best fit line | ≥ 85 %ile | $\overline{X}$, mdn, best fit line | ≥ 85 %ile | $\overline{X}$, mdn, best fit line | ≥ 85 %ile | $\overline{X}$, mdn, best fit line | ≥ 85 %ile | $\overline{X}$, mdn, best fit line | ≥ 85 %ile | $\overline{X}$, mdn, best fit line | ≥ 85 %ile |
| **VERY DARK SURROUND** | | | | | | | | | | | | | | | |
| A (.11) | Allen & Straub (1955) | | | 0.20 | | 0.80 | | | | | | | | | |
| - (.125) | Hind et al. (1976) | | | | | | | 0.29 | | 2.74 | | | | | |
| C (.143) | Allen & Straub (1955) | | | | | 0.20 | | 0.55 | | 7.2 | | | | | |
| - (.167) | Hind et al. (1976) | | | | | | | 0.29 | | 1.8 | | | | | |
| F (.187) | Allen & Straub (1955) | | | | | | | 0.12 | | 0.25 | | 0.57 | | 1.9 | |
| - (.2) | Allen (1958) | | | 0.07 | | 0.19 | | 0.40 | | 0.95 | | 3.1 | | | |
| - (-) | Smyth (1947) | | | | | | | | 2.3 | | | | | | |
| **DARK SURROUND** | | | | | | | | | | | | | | | |
| E (.172) | Allen et al. (1967) | | | | | 0.34 | | 1.47 | | | | | | | |
| - (.2) | Van Norren (1981) | 0.04 | | 0.08 | | 0.19 | | 0.76 | | 1.90 | | 7.6 | | 38.0 | |
| **MODERATE SURROUND** | | | | | | | | | | | | | | | |
| A (.11) | Allen & Straub (1955) | | | 0.24 | | 0.84 | | | | | | | | | |
| C (.143) | Allen & Straub (1955) | | | | | 0.24 | | 0.55 | | 6.4 | | | | | |
| E (.172) | Allen et al. (1967) | | | 0.40 | | 0.87 | | 2.0 | | 11.5 | | | | | |
| F (.187) | Allen & Straub (1955) | | | | | | | 0.16 | | 0.33 | | 0.67 | | 2.3 | |
| - (.2) | Forbes et al. (1976)lab[1] | 1.8 | | 34.0 | | | | | | | | | | | |
| - (.2) | Olson & Bernstein (1977)[1] | | | | | | | | 0.057 | | 0.57 | | | | |
| - (.2) | Van Norren (1981) | 0.06 | | 0.13 | | 0.32 | | 1.28 | | 3.21 | | 12.9 | | 64.2 | |
| **BRIGHT SURROUND** | | | | | | | | | | | | | | | |
| - (-) | Smyth (1947) | | | | | | | | 5.0 | | | | | | |
| **VERY BRIGHT SURROUND** | | | | | | | | | | | | | | | |
| E (.172) | Allen et al. (1967) | 0.34 | | 0.78 | | 2.0 | | 5.7 | | 16.0 | | | | | |
| - (.2) | Van Norren (1981) | 0.23 | | 0.46 | | 1.16 | | 4.64 | | 11.6 | | 46.4 | | 232.0 | |

1Range of surround conditions collapsed.

Table 18. Legibility performance as a function of sign luminance (fL) (continued): white on blue.

| LETTER SERIES (SW/H) | SOURCE | 20 ft/in | | 30 ft/in | | 40 ft/in | | 50 ft/in | | 60 ft/in | | 70 ft/in | | 80 ft/in | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile |
| **VERY DARK SURROUND** | | | | | | | | | | | | | | | |
| C (.143) | Hills & Freeman (1970)* | | | 0.125 | | 0.31 | | 0.77 | | | | | | | |
| **MODERATE SURROUND** | | | | | | | | | | | | | | | |
| - (.2) | Forbes et al. (1976)lab[1] | | | 4.2 | | 28.0 | | | | | | | | | |
| - (.2) | Olson & Bernstein(1977)[1,2] | | | | | | | | 0.12 | | 0.972 | | 12.0 | | |

[1]Range of surround conditions collapsed.
[2]Legend to background luminance ratio is 12:1.

white on green.

| LETTER SERIES (SW/H) | SOURCE | 20 ft/in | | 30 ft/in | | 40 ft/in | | 50 ft/in | | 60 ft/in | | 70 ft/in | | 80 ft/in | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile |
| **VERY DARK SURROUND** | | | | | | | | | | | | | | | |
| C (.143) | Hills & Freeman (1970)[3] | | | 0.15 | | 0.34 | | 2.92 | | | | | | | |
| **MODERATE SURROUND** | | | | | | | | | | | | | | | |
| - (.2) | Forbes et al. (1976) lab[1] | 1.2 | | 10.0 | | 80.0 | | | | | | | | | |
| - (.2) | Forbes et al.(1976) field[1] | | | | | | 0.70 | 0.80 | 2.7 | | | | | | |
| - (.2) | Olson & Bernstein(1977)[1,3] | | | | | | | | 0.246 | | 0.858 | | | | |

[1]Range of surround conditions collapsed.
[3]Legend to background luminance ratio is 6:1.

Table 18. Legibility performance as a function of sign luminance (fL) (continued): white on red.

| LETTER SERIES (SW/H) | SOURCE | 20 ft/in | | 30 ft/in | | 40 ft/in | | 50 ft/in | | 60 ft/in | | 70 ft/in | | 80 ft/in | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile |
| **VERY DARK SURROUND** | | | | | | | | | | | | | | | |
| C (.143) | Hills & Freeman (1970)[4] | | | 0.21 | | 0.93° | | | | | | | | | |
| **MODERATE SURROUND** | | | | | | | | | | | | | | | |
| - (.2) | Olson & Bernstein(1977)[1,4] | | | | | | 0.128 | | 1.2 | | | | | | |

[1]Range of surround conditions collapsed.
[4]Legend to background luminance ratio is 4:1.
°Curve drops below 40 ft/in performance level and then rises above it again at 4.3 fL.



color combinations collapsed.

| LETTER SERIES (SW/H) | SOURCE | 20 ft/in | | 30 ft/in | | 40 ft/in | | 50 ft/in | | 60 ft/in | | 70 ft/in | | 80 ft/in | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile | $\bar{X}$, mdn, best fit line | ≥ 85 %ile |
| **VERY DARK SURROUND** | | | | | | | | | | | | | | | |
| - (-) | Richardson (1976) | | | | | | | 0.27 | | 1.31 | | 1.67 | | | |

Note: 1 ft/in = 0.12 m/cm; 1 fL = 0.318 cd/ft$^2$ = 3.43 cd/m$^2$.

However, even after adjusting for the effects of these kinds of factors, the data remain disconcertingly inconsistent. Because of this, any MLRL analytically derived from these studies are dubious and require thorough validation prior to application. Nevertheless, many of the inconsistencies in the data can be identified and then disregarded by assessing the available data in terms of documented principles of legibility performance. The following general principles, then, comprise the logic for selecting luminance requirements from the morass of disparate findings:

- As required legibility performance increases from 20 through 80 ft/in (2.4 through 9.6 m/cm), MLRL should increase.
- As letter series progresses from A through F to Landolt C (i.e., as SW/H increases from 0.11 through 0.172 to 0.2), MLRL should decrease.
- MLRL should be higher for black-on-white signs than for white-on-black signs.
- MLRL should increase from black-on-white, through black-on-orange, to black-on-yellow signs.
- MLRL should increase from white-on-blue, through white-on-green, to white-on-red signs.

For the most part, these principles are the conclusions derived from the observations described in figure 9. The logic of these general principles, then, provided the means for analytically deriving the MLRL from the data in table 18. These MLRL are presented in table 19.

Table 19. Analytically derived minimum luminance requirements for legibility (MLRL): unit of measure is fL.

| COLOR COMBINATION | LETTER SERIES (SW/H) | REQUIRED LEGIBILITY PERFORMANCE | | | | | | | SOURCE | PERFORMANCE CRITERION | SURROUND LEVEL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 20 ft/in | 30 ft/in | 40 ft/in | 50 ft/in | 60 ft/in | 70 ft/in | 80 ft/in | | | |
| Black-on-White | A (.11) | | 0.30 | 5.3 | | | | | Allen & Straub (1955) | best fit line | moderate |
| | B (.125) | | | | 1.05 | | | | Hind et al. (1976)[1] | median | very dark |
| | C (.143) | | | 3.0 | 0.94 | 64.0® | | | Allen & Straub (1955) | best fit line | moderate |
| | E (.172) | | | | 0.75 | | | | Hind et al. (1976)[2] | median | very dark |
| | E (.172) | [0.27] | [0.77] | [2.4] | [15.6]• | | | | Allen et al. (1967) | best fit line | moderate |
| | F (.187) | | | | 0.17 | 0.46 | 1.50 | 10.0 | Allen & Straub (1955) | best fit line | moderate |
| | - (.2) | | | 0.027 | 0.084 | 0.44 | 1.50 | | Olson & Bernstein (1977) | 85%ile | range collapsed |
| Black-on-Orange | - (.2) | | | 0.08 | 0.24 | 0.9 | 2.2 | | Olson & Bernstein (1977) | 85%ile | range collapsed |
| Black-on-Yellow | - (.2) | | | 0.1 | 0.38 | 1.4 | 2.2 | | Olson & Bernstein (1977) | 85%ile | range collapsed |
| | - (.2) | | | [0.43] | [1.3] | | | | Forbes et al. (1976) field | 85%ile | range collapsed |

[]Values in brackets, [], are derived from dynamic field studies; all other values are derived from static laboratory studies. These data suggest that laboratory-derived requirements should be increased by a factor somewhere between 2 and 10 in order to accommodate driver needs under dynamic field conditions.

1 These data are derived from stimuli with SW/H of 0.125; these stimuli were not series B letters, but were close.

2These data are derived from stimuli with SW/H of 0.167; these stimuli were not series E letters, but were close.

®This value appears to be spuriously high and should probably be omitted.

• This value is inconsistent with data obtained under different surround conditions within the same study; a more consistent entry for this cell is about 7.0.

Note: 1 ft/in = 0.12 m/cm; 1 fL = 0.318 cd/ft$^2$ = 3.43 cd/m$^2$.

Table 19. Analytically derived minimum luminance requirements for legibility (MLRL): unit of measure is ftL (continued).

| COLOR COMBINATION | LETTER SERIES (SW/H) | REQUIRED LEGIBILITY PERFORMANCE 20 ft/in | 30 ft/in | 40 ft/in | 50 ft/in | 60 ft/in | 70 ft/in | 80 ft/in | SOURCE | PERFORMANCE CRITERION | SURROUND LEVEL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| White-on-Black | A (.11) | | 0.24 | 0.84 | | | | | Allen & Straub (1955) | best fit line | moderate |
| | B (.125) | | | | 0.29* | 2.74 | | | Hind et al. (1976)[1] | median | very dark |
| | C (.143) | | | 0.24 | 0.55 | 6.4** | | | Allen & Straub (1955) | best fit line | moderate |
| | E (.172) | | | | 0.29 | 1.8 | | | Hind et al. (1976)[2] | median | very dark |
| | E (.172) | | [0.40] | [0.87] | [2.0] | [11.5] | | | Allen et al. (1967) | best fit line | moderate |
| | F (.187) | | | | 0.16 | 0.33 | 0.67 | 2.3 | Allen & Straub (1955) | best fit line | moderate |
| | - (.2) | | | | 0.057 | 0.57© | | | Olson & Bernstein (1977) | 85%ile | range collapsed |
| | - (.2) | | | [0.07] | [0.19] | [0.40] | [0.95] | [3.1] | Allen (1958) | mean | very dark |
| White-on-Blue | C (.143) | | 0.125 | 0.31 | 0.77 | | | | Hills & Freeman (1970) | mean | not indicated |
| | - (.2) | | | | 0.12 | 0.972 | 12.0 | | Olson & Bernstein (1977) | 85%ile | range collapsed |
| White-on-Green | C (.143) | | 0.15 | 0.34 | 2.92 | | | | Hills & Freeman (1970) | mean | not indicated |
| | - (.2) | | | | 0.246 | 0.858™ | | | Olson & Bernstein (1977) | 85%ile | range collapsed |
| | - (.2) | | | [0.70] | [2.7] | | | | Forbes et al. (1976) field | 85%ile | range collapsed |
| White-on-Red | C (.143) | | 0.21 | 0.93 | | | | | Hills & Freeman (1970) | mean | not indicated |
| | - (.2) | | | 0.128 | 1.2 | | | | Olson & Bernstein (1977) | 85%ile | range collapsed |

*MLRL should increase from series C to series B letters; the entry for this cell should logically be greater than 0.55.

**MLRL should increase from series E, through series C, to series B letters; the entry for this cell should logically be between 1.8 and 2.74.

©MLRL should increase as SW/H decreases from 0.2 to 0.187, and when SW/H is constant at 0.2, the laboratory requirement of 0.57 should be less than the field requirement [0.40]; the entry for this cell should logically be less than 0.33.

™MLRL should increase from white-on-blue to white-on-green signs; the entry for this cell should logically be greater than 0.972.

## APPENDIX B: Luminance of Retroreflective Materials and their Deterioration

### 1. Standards

The performance requirements for new retroreflective sheeting used for traffic control signs are given in "Federal Specification FP-79" (sections 633 and 718) and "Federal Specification L-S-300C."(34,37) To ensure compliance with the cited standards there are a number of test procedures and methods to be followed, including "Federal Test Methods Standards 370 and 141"; and "ASTM E97 and G23."(38,39,40,41) These standards, methods, and procedures necessarily attend to those sheeting attributes that are readily discernible through observation, instrumental testing, and simulation. On the surface, they appear to represent the range of performance requirements demanded of sheeting upon delivery as well as in use. Unfortunately, the specifications do not readily permit translation of the test data to the field. In fact, "ASTM G23-81" section 2.2 cautions:

> Since the natural environment varies with respect to time, geography, and topography, it may be expected that the effects of natural exposure will vary accordingly. All materials are not affected equally by the same environment. Results obtained by use of this practice should not be presented as equivalent to those of any natural weathering test until the degree of quantitative correlation has been established for the material in question.(41)

Literature available from independent sources is also lacking in information necessary to establish the degree of quantitative correlation.

### 2. Retroreflective Performance

There are two distinct reflective intensity thresholds specified in "FP-79" that must be met by types II and III sheeting.(34) They provide minimum values for acceptance performance and performance after accelerated weathering. The values are given as specific intensity per unit area (SIA), expressed as candelas of reflected light per footcandle of incidence light per square foot of target ($cd/fc/ft^2$).[1] The "FP-79" minimum SIA acceptance

[1] 1 $cd/ft^2$ = 10.76 $cd/m^2$; 1 fc = 1 $lumen/ft^2$ = 10.76 $lumen/m^2$.

values are shown in table 20 for types II and III sheeting. It was necessary to calculate the SIA values shown in table 21 for the accelerated weathering performance, since they are stated in "FP-79" as a percentage of the acceptance SIA; that is, type II will retain not less than 50 percent of the minimum SIA of table 20 after 1,000 hours of weatherometer exposure, and type III will retain not less than 80 percent of the minimum SIA of table 20 after 2,200 hours[2] of weatherometer exposure.

Tables 20 and 21 give the minimum Federal standards, and also represent the reflective brightness values given by manufacturers in their product literature. A survey of manufacturer product literature revealed that brightness values for the available materials are presented not as actual values, but as "meeting or exceeding the Federal specifications." Seibulite states that their type II sheeting ". . . conforms with practically all specifications for reflectivity throughout the world" ("Bulletin #10," 1980); Avery International states that "Fasign specification grade (type II) meets Federal Specs L-S-300C and FP-79" ("Product Information Brochure," 1982); and 3M goes one step further by including the Federal minimum SIA values as a table in their literature for type II and type III sheeting ("Bulletin 85, Attachment #1"; "Bulletin 102, Attachment #1").[42,43,44] In only one case, for Seibulite super engineering grade sheeting, appropriately classed as type IIB, were SIA values given that differed from the Federal specifications. The SIA values shown in table 22, although different from any Federal specification, are again expressed as minimum.

Table 22. Specific intensity (SIA) minimum of Seibulite super engineering grade sheeting.

| Observation Angle | Entrance Angle | White | Yellow | Green |
|---|---|---|---|---|
| 0.2° | - 4° | 140 | 70 | 30 |
| | 30° | 65 | 33 | 8 |
| 0.5° | - 4° | 48 | 30 | 7 |
| | 30° | 28 | 18 | 3.5 |

2 After 500 hours for orange.

Table 20. Acceptance standards for specific intensity per unit area (SIA) specified in "FP-79" for type II and III sheeting.

| Observation Angle (°) | Entrance Angle (°) | MINIMUM SPECIFICATIONS FOR SPECIFIC INTENSITY PER UNIT AREA (SIA) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | White | | Red | | Green | | Blue | | Orange | | Yellow | |
| | | Type II | Type III | Type II | Type III | Type II | Type III | Type II | Type III | Type II | Type III | Type II | Type III |
| 0.2 | - 4 | 70 | 250 | 14.5 | 45 | 9.0 | 45 | 4.0 | 20.0 | 25.0 | 100 | 50 | 170 |
| 0.2 | + 30 | 30 | 150 | 6.0 | 25 | 3.5 | 25 | 1.7 | 11.0 | 7.0 | 60 | 22 | 100 |
| 0.5 | - 4 | 30 | 95 | 7.5 | 15 | 4.5 | 15 | 2.0 | 7.5 | 13.5 | 30 | 25 | 62 |
| 0.5 | + 30 | 15 | 65 | 3.0 | 10 | 2.2 | 10 | 0.8 | 5.0 | 4.0 | 25 | 13 | 45 |

Table 21. Accelerated weathering acceptance standards for specific intensity per unit area (SIA) specified in "FP-79" for type II[1] and III[2] sheeting.

| Observation Angle (°) | Entrance Angle (°) | MINIMUM SPECIFICATIONS FOR SPECIFIC INTENSITY PER UNIT AREA (SIA) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | White | | Red | | Green | | Blue | | Orange | | Yellow | |
| | | Type II | Type III | Type II | Type III | Type II | Type III | Type II | Type III | Type II | Type III[3] | Type II | Type III |
| 0.2 | - 4 | 35.0 | 200 | 7.3 | 36 | 4.5 | 36 | 2.0 | 16.0 | 12.5 | 80 | 25.0 | 136.0 |
| 0.2 | + 30 | 15.0 | 120 | 3.0 | 20 | 1.8 | 20 | 0.9 | 8.8 | 3.5 | 48 | 11.0 | 80.0 |
| 0.5 | - 4 | 15.0 | 76 | 3.8 | 12 | 2.3 | 12 | 1.0 | 6.0 | 6.8 | 24 | 12.5 | 49.6 |
| 0.5 | + 30 | 7.5 | 52 | 1.5 | 8 | 1.1 | 8 | 0.4 | 4.0 | 2.0 | 20 | 6.5 | 36.0 |

[1]Type II 50 percent of table 20 at 1,000 hours of weatherometer exposure.

[2]Type III 80 percent of table 20 at 2,200 hours of weatherometer exposure.

[3]80 percent of table 20 at 500 hours of weatherometer exposure.

The discussion of minimum specifications provides a frame of reference for examining the actual reflective intensity of type II and III sheeting. From the available literature, personal communications with manufacturers, raw acceptance testing data provided by the Louisiana DOT, and durability data provided by 3M, it appears that the reflective brightness of new sheeting is almost always in excess of the minimum specifications. This is true even when type II and type III sheeting are evaluated in use. Reflective intensity values in excess of specifications for new sheeting have occurred even after 15 years of exposure. The field exposure findings should be treated cautiously however, since they do not represent values to be expected. Rather, they represent what is possible in some cases.

Table 23 summarizes the Louisiana acceptance testing data for type II sheeting submitted by three manufactuers (Kiwa Chemical, Morgan Adhesives, and Avery International), in six colors (silver-white, red, green, blue, orange, yellow).[(45)] Two types of adhesive (heat applied [HA] and pressure sensitive [PS]) were used. In all but two cases, regardless of color, manufacturer, or adhesive, the measured reflective intensity was greater than minimum specification. In one case it was 700 percent greater!

The information in figure 10 presents median weathering data of type II and type III sheeting contrasted with the warranted performance.[(13)] Although the sheeting color is not specified, it can be assumed to be silver-white for both sheeting types based on the original reflective intensity values. "FP-79" values (cd/fc/$ft^2$) for new white sheeting are 70 for type II and 250 for type III.[3] Both sheeting types, when new, demonstrate retroreflective performance greater than the minimum specified and still do even after extended exposure.

In a personal communication, a representative of Avery International (Fasign sheeting) disclosed that their sheeting is manufactured to be in excess of the Federal standards. An example used was white, type II sheeting. Avery generally produces it to perform at 100-110 cd/fc/$ft^2$, which is in excess (142.9 to 157.1 percent) of the 70 cd/fc/$ft^2$ "FP-79" minimum.[3]

[3]Note: 1 cd/$ft^2$ = 10.76 cd/$m^2$; 1 fc = 1 lumen/$ft^2$ = 10.76 lumen/$m^2$.

Table 23. Actual SIA expressed as a percentage of the minimum specified SIA from "FP-79" for new type II sheeting.

| Color<br>Manufacturer/ (Adhesive)[1] | % of Minimum Specified Reflective Intensity | | | |
|---|---|---|---|---|
| | 0.2° Obs Angle | | 0.5° Obs Angle | |
| | -4° Ent Angle | +30° Ent Angle | -4° Ent Angle | +30° Ent Angle |
| **Silver-White** | | | | |
| Mfg 1 (HA) | 110.9 | 185.7 | 119.3 | 212.0 |
| " 2 (HA) | 146.6 | 198.0 | 138.0 | 276.0 |
| " 3 (HA) | 148.6 | 253.3 | 160.0 | 300.0 |
| " 1 (PS) | 125.1 | 192.3 | 132.7 | 225.3 |
| " 2 (PS) | 154.3 | 258.0 | 156.0 | 312.0 |
| " 3 (PS) | 157.1 | 263.3 | 150.0 | 260.0 |
| **Red** | | | | |
| Mfg 1 (HA) | 211.0 | 293.3 | 173.3 | 310.0 |
| " 2 (HA) | 198.6 | 326.7 | 144.0 | 360.0 |
| " 3 (HA) | 164.8 | 305.0 | 168.0 | 373.3 |
| " 1 (PS) | 204.1 | 261.7 | 173.3 | 310.0 |
| " 2 (PS) | 136.6 | 210.0 | 120.0 | 300.0 |
| " 3 (PS) | 193.8 | 328.3 | 186.7 | 426.7 |
| **Green** | | | | |
| Mfg 1 (HA) | 350.0 | 422.9 | 328.9 | 422.7 |
| " 2 (HA) | 180.0 | 437.1 | 200.0 | 286.4 |
| " 3 (HA) | 265.6 | 360.0 | 280.0 | 381.8 |
| " 1 (PS) | 287.8 | 317.1 | 246.7 | 336.4 |
| " 2 (PS) | 180.0 | 308.6 | 180.0 | 245.5 |
| " 3 (PS) | 296.7 | 400.0 | 280.0 | 445.5 |
| **Blue** | | | | |
| Mfg 1 (HA) | 392.5 | 547.1 | 370.0 | 575.0 |
| " 2 (HA) | 270.0 | 317.6 | 225.0 | 450.0 |
| " 3 (HA) | 140.0 | 164.7 | 210.0 | 350.0 |
| " 1 (PS) | 392.5 | 547.1 | 370.0 | 700.0 |
| " 2 (PS) | 225.0 | 317.6 | 180.0 | 450.0 |
| " 3 (PS) | 140.0 | 164.7 | 210.0 | 350.0 |
| **Orange** | | | | |
| Mfg 1 (HA) | 170.8 | 320.0 | 173.3 | 382.5 |
| " 2 (HA) | 180.0 | 385.7 | 173.3 | 450.0 |
| " 3 (HA) | 182.8 | 454.3 | 161.5 | 495.0 |
| " 1 (PS) | 154.8 | 320.0 | 151.1 | 382.5 |
| " 2 (PS) | 93.6 | 282.9 | 66.7 | 225.0 |
| " 3 (PS) | 246.0 | 538.6 | 235.6 | 645.0 |
| **Yellow** | | | | |
| Mfg 1 (HA) | 170.4 | 202.3 | 214.8 | 327.7 |
| " 2 (HA) | 169.2 | 335.5 | 115.2 | 207.7 |
| " 3 (HA) | 146.0 | 204.5 | 156.0 | 215.4 |
| " 1 (PS) | 185.5 | 202.3 | 155.6 | 199.2 |
| " 2 (PS) | 205.2 | 343.6 | 187.2 | 304.6 |
| " 3 (PS) | 158.0 | 218.2 | 148.0 | 215.4 |

[1] HA means heat applied; PS means pressure sensitive.

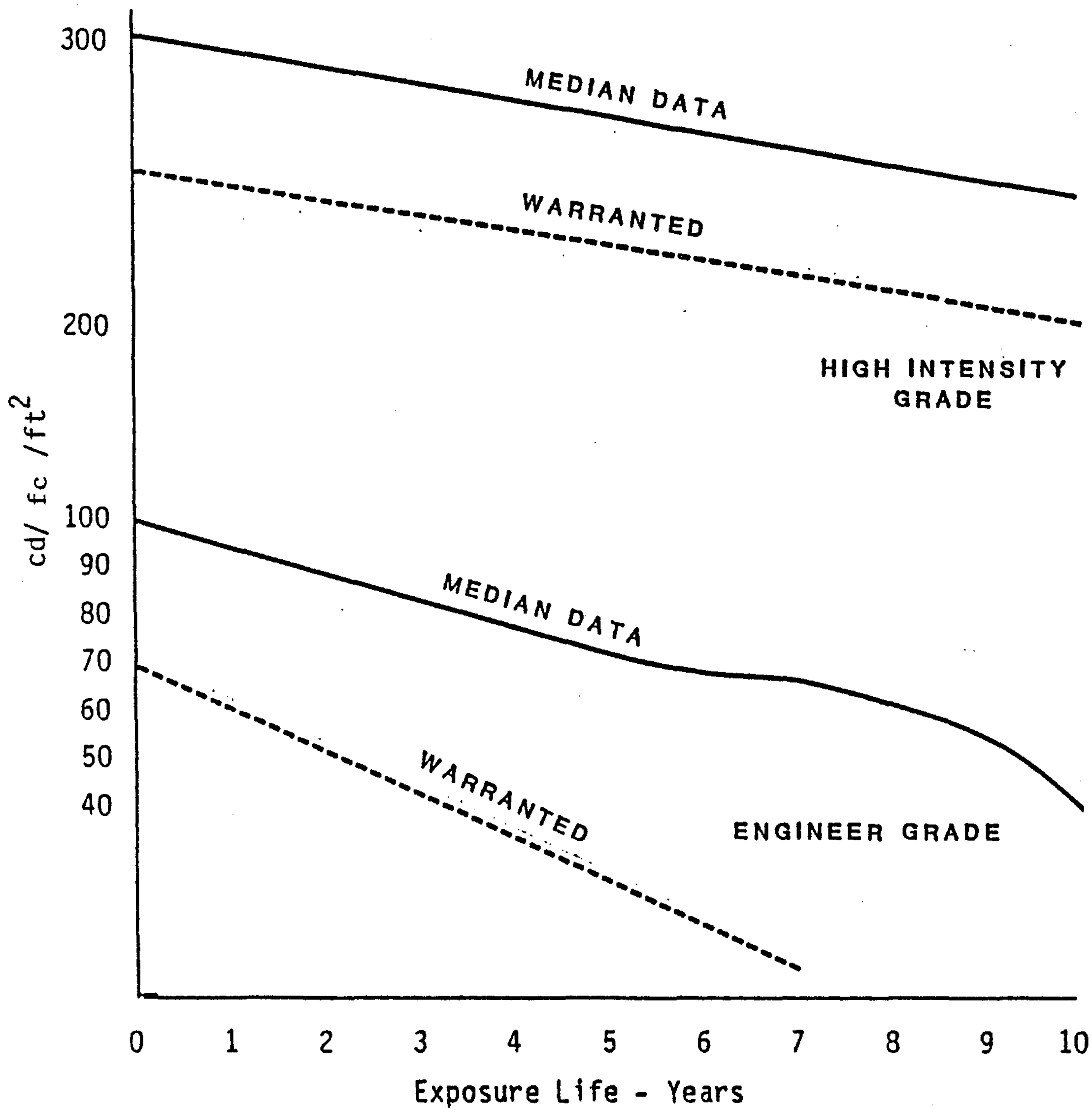



Figure 10. Median weathering data and warranty statement--type II and type III sheeting (3M Corporation data).

Note: 1 $cd/ft^2$ = 10.76 $cd/m^2$; 1 fc = 1 $lumen/ft^2$ = 10.76 $lumen/m^2$.

One cause of the difference is that Avery is on the accepted suppliers list of the Pennsylvania (PA) DOT. The PADOT standards for white sheeting are more stringent, being 128.6 percent of the Federal; there is no difference for other colors. Consequently, manufacturers must make a product that is ensured of compliance with the more stringent standards.

The implication is that within a class, i.e., type II and III sheeting, the potential exists for sheeting to meet or exceed the "new" retroreflective performance requirements even after a number of years in use.

3. Accelerated Weathering

Various methods are employed for assessing the durability of retroreflective sheeting. Accelerated weathering via simulation (weatherometer) is called for in the Federal standards, but manufacturers generally reject weatherometer data and agree that there is no substitute for natural weathering. However, in the absence of natural weathering data, manufacturers feel the next best method is some form of accelerated outdoor test. In fact, they rely heavily on accelerated outdoor weathering tests for the product durability claims they make.

Weatherometer exposure has limited application to real sheeting performance for a number of reasons. No standard exists that allows comparison to real performance. There are references in the literature to conversion factors, but the means of derivation are not specified. One researcher claims that 1 hour in the weatherometer is equivalent to 18 hours of normal weathering (Robertson, 1973), and a manufacturer, via technical bulletin, says, ". . . this instrument appears to accelerate degradation about 25 times compared to natural outdoor weathering (Avery International, 1983).[46,47] Further, there are many interactive conditions which influence deterioration in the field but which cannot be duplicated in a weatherometer. Also, conditions (e.g., ultraviolet wavelengths below 290 nanometers) occur in a weatherometer that do not occur in nature.

Outdoor exposure facilities (weathering stations) have a broad range of weathering acceleration capability. Some of the more common accelerated tests include:

- Stationary, vertical, south-facing racks.
- Stationary, 45 degrees from horizontal, south-facing racks.
- Equatorial mount--or follow-the-sun rack-- which keeps test panel at approximately 90 degrees to the sun's rays.
- EMMA--equatorial mount with mirrors.
- EMMAQUA--Same as EMMA plus water spray.

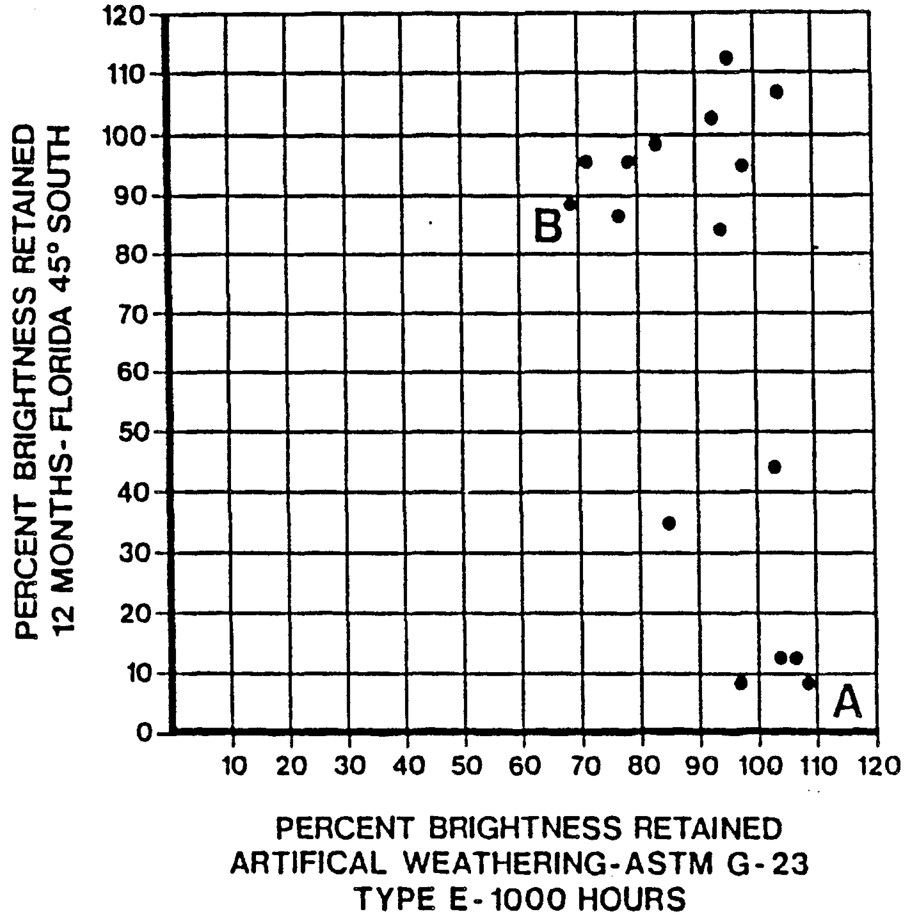
Accelerated weathering rates are listed, based on comparative tests, as being 3 to 13 times faster than similar tests on stationary 45 degree, south racks (Avery International, 1983).[47] However, the rates are expressed with no apparent conversion, although the fact that these tests occur outdoors fosters more confidence in their predictive value than weatherometer tests. Figure 11, from a 3M technical memo, addresses this point.[48]

The data in figure 11 are from a study in which several reflective sheeting samples of unknown composition were compared in an accelerated weathering device (weatherometer; 1000 hours) and in Florida for 1 year facing south at 45 degrees of inclination.

## 4. Durability and Deterioration

Durability and resistance to deterioration are not synonymous. Deterioration is the term generally applied when talking about the retroreflective properties of sheeting. Durability generally is the term used by manufacturers to warrant their products, or to describe the degradation of all components of sheeting; thus, deterioration is necessarily included. A further distinction between the terms is that durability statements are usually based on accelerated weathering tests (which, as noted previously, have real application problems), while deterioration is measured via some form of photometric testing.

# PERCENT BRIGHTNESS RETAINED 12 MONTHS FLORIDA VS. 1000 HOURS ARTIFICIAL WEATHERING




Examples of How to Read This Graph

Sample A

Retained 110% of its original brightness when exposed for 1000 hours in the artificial weathering device (i.e., it gained 10%) while it retained only 8% of its original brightness when exposed for 1 year in Florida facing south at 45° inclination.

Sample B

Retained only 69% in the artificial weathering device whereas it retained 89% in Florida.

Figure 11. Accelerated weathering: weatherometer versus Florida, 45 degrees, south.

Further, sheeting deterioration is an interactive process of many variables. Some include:

- Material (sheeting type).
- Manufacturer.
- Color.
- Adhesive type.
- Fabrication and handling techniques.
- Damage.
- Substrate (backing).
- Sunlight.
- Orientation to sun.
- Airborne abrasives.
- Air pollution.
- Proximity to road.
- Climate.
- Temperature.
- Salt spray.

As can be expected, there is a lack of comprehensive studies which attend to all the interactive variables. This is not to say that sheeting deterioration rates cannot or have not been posited.

Table 24 reports the effective service life (durability) for types II and III sheeting from a number of sources. This information is representative of the variability found in the literature and is reported as illustrative rather than definitive. Direct comparison of the data is difficult, if not impossible, because of the different standards and methods employed for the determination of the effective service life rates given. For example, some rates were determined via simulation (accelerated weathering), some via "reliable tests," some based on actual service life, and some on survey responses. In all cases, regardless of measurement technique, the conversion to years of effective service life was made either by the respective author or by using a metric provided by the respective author. Further, the data is generic, presented by sheeting type (as defined in "FP-79") only.

Table 24. Effective service life of "FP-79" type II and type III sheeting.

| SOURCE | Effective Service Life | | | BASIS |
|---|---|---|---|---|
| | Type II (Engineering Grade) | Type IIB[1] (Super Engineering Grade) | Type III (High Intensity Grade) | |
| Avery International (1982) | 7 years | | | Tests Believed To Be Reliable |
| Kenyon et al. (1982) | 5-13 years with 15-plus years possible | | | Historical Data Instrumental Measures Engineering Opinion |
| Olson & Bernstein (1977) | 3-10 years | | Not enough experience to evaluate | Questionnaire Data (38 Agencies and Turnpike Authorities) |
| Rizenbergs (1972) | 9 years | | 23 years | Weatherometer |
| Rizenbergs (1974) | 6 years | | 12-18 years | Weatherometer |
| Seibulite (1980) | 7 years | 10 years | | Weatherometer Outdoor Weathering (45° South) EMMAQUA |
| Sorenson et al. (1978) | 7-10 years[2] 10-12 years[2] | 10-12 years | 10-12 years | Manufacturers Estimates Weathering Station Operational Experience |
| 3M (1982) | 7 years (5 years orange) | | 10 years (3 years orange) | Experience and Tests Believed To Be Reliable |

[1]Not listed in "FP-79." Super engineering grade is a hybrid.
[2]Different manufacturers.

This gross classification doesn't attend to differential deterioration rates as a function of color, adhesive type, or manufacturer, which are identified in the literature as being instrumental in the effective service life of different brands of sheeting. The necessary data is just unavailable. The only common ground that can be found in table 24 is that the rates given assume vertical exposure on stationary objects, and that end of service life (or failure) is determined (at least in part) by some maximum level of retroreflective deterioration based on photometric measures.

The effective service life is stated in the literature to be 7 years for type II sheeting, 10 years for type IIB (super engineering grade), and 10 years for type III as cited in table 24. The durability of orange sheeting is less, varying from 3 to 5 years. These appear to be conservative estimates based on other studies cited. Service lives of 15 years or more for type II sheeting were noted in one field study (Kenyon et al., 1982), where the reflective intensities in most cases were at or above new specifications.[(49)] The design of the study had some problems though, since data on installation were available for only 29.6 percent of the signs surveyed. Rizenbergs (1972), using weatherometer data, found that type III sheeting, depending on color, demonstrated performance two and one half times that of type II for an estimated service life of 23 years![(50)] However, 2 years later, Rizenbergs (1974) downgraded his own estimates of effective service life to 6 years for type II and 12 to 18 years for type III.[(51)] On the other hand, the service lives given in the product literature could be viewed as optimistic when compared with the other studies cited.[(42,43,44)] Kenyon et al. (1982) identified actual service lives of as few as 5 years, and Olson and Bernstein (1977) reported service life (based on a questionnaire submitted to 49 agencies and turnpike authorities) as short as 3 years.[(49,8)] The points to be made are that the determination of the effective service life of reflective sheeting is a difficult and sometimes confusing task, and that the manufacturers' estimates are probably as good as any for the time being.

All of the discussion thus far has focused on irreversible deterioration. There are also forms of reversible, often self-reversing, deterioration caused by dirt, dew, and front. Dirt accumulation can severely degrade the brightness of a sign. It also changes the brightness contrast by making the sign colors more uniform. However, Kenyon et al. (1982) found that spring rains restored most of the signs studied to within 15 percent of their washed brightness values.(49) Both values fell within acceptable limits in most cases, and signs that would benefit from washing (generally necessary only during winter months) can be identified from daytime inspection. It should be noted that this study did not include construction and maintenance signs which may merit working under a wider range of conditions.

Lowden and Stoker (1971), in a study of the effects of dew on reflective sign materials, concluded that the principal deterrent to effective reflectance was moisture droplets scattering the light rather than a film of water causing mirror-like reflection (refraction rather than reflection).(52) They also found that it appears frost darkens signs more than dew, and that frequently the reflectance loss is not uniform across the face of a sign for either condition. Though transient, the problem of frost and dew is severe as described by Sorenson et al. (1978): ". . . under heavy dew and frost the reflectivity of a sign can approach zero."(53) Although severe, the frequency of the problem appears limited based on work by Woltman (1965).(54) He concluded that the average sign backing was free of dew 90.4 percent of the time during the study, and that when dew was observed it occurred, on the average, 6 hours after sunset and was of 2.5 hours in duration.

5. Determination of Field Deterioration Rate

The durability of reflective sheeting is most frequently discussed in terms of decreased reflective intensity over time, and is assumed to be a critical factor in sign replacement. However, there are many other factors which necessitate sign replacement, often before any luminance deterioration occurs. One of the most pronounced is sign vandalism. Based on responses from 30 of the 50 states, approximately 1.2 million traffic signs were replaced during 1980. Of the number replaced, approximately 28 percent were replaced because of vandalism (Chadda and Carter, 1983).(55) Further, data obtained in Idaho show that for four basic categories of sign replacement (obsolescence, damage, new construction, and delamination and reflectivity) most of the signs were replaced because of obsolescence (MUTCD change, legislation, etc.) or damage.(56) Only a small percentage was replaced because of sheeting deterioration (delamination and reflectivity category). The conditions which cause sign replacement (often before sheeting deterioration) could therefore hamper efforts towards the determination of the effective field service life of sheeting.

Further, much is known about the performance of reflective sheeting in accelerated testing situations; the conditions are known, controllable, and measurable. However, field deterioration rates are difficult to address, since many naturally occurring, uncontrollable factors, acting either singly or in concert, produce deterioration. This can result in differential rates and types of material decay depending on which factors are operative and interactive. Consequently, it is possible to have material degradation of sufficient magnitude to warrant sign replacement even though the luminance deterioration threshold has not been reached.

Given the natural weathering phenomena (sun, wind, rain, abrasion, salt, temperature, etc.) and the fact that deterioration is an interactive process, the prediction of irreversible deterioration of the retroreflective properties in the field is difficult at best. Examination of isolated variables appears to have limited utility. Classification variables which represent multidimensional measurement seem to have the greatest potential for assessing irreversible deterioration of the retroreflective properties of sheeting in use. They include:

- Sheeting type and manufacturer.
- Sheeting color.
- Sheeting adhesive.
- Substrate (sign backing).
- Sign orientation to sun.
- Geographic zone.
- Environment (industrial, non-industrial).
- Sign location (placement [overhead, shoulder] and lateral offset).

Each of these represents a factor which could be represented as several variables. The factors are more readily observed and recorded and therefore easier to use than the underlying variables (e.g., hours of sunlight, angle of sun, chemical composition of air, etc.).

Sheeting type, manufacturer, color, adhesive type, and substrate all represent sheeting and sign characteristics. Similar products from different manufacturers have performed differently. The sheeting colors deteriorate at different rates as an interactive function of sunlight and pigment. Adhesive type can affect performance as a result of the mounting process (heat, no heat) and can interact with the substrate, and the substrate itself can precipitate deterioration due to thermal expansion and contraction different from the sheeting.

Key weather conditions are incorporated in orientation to the sun and geographic zone. Sign orientation to the sun is emphasized in most discussions of sheeting deterioration, particularly with accelerated outdoor tests, although one study found no effect (Kenyon et al., 1982).[49] This study, however, had some flaws in its design which make the results questionable. Geographic zone has been shown to be important to sheeting performance, particularly since manufacturers warrant different performance for different areas of the country, or state performance qualifiers based on geographic location of use. That is, in areas where heavy snow or extreme sun prevail, sheeting is expected to provide shorter effective service life.

The environment and sign location classifications encompass many of the interactive variables which foster deterioration. For example, pollutants and dirt in industrial areas affect sheeting more than in nonindustrial areas. Further, sign proximity to the road has been shown to affect sheeting; generally, the closer the road, the faster the deterioration.

These classification variables therefore appear to have potential for the determination of irreversible retroreflective deterioration of sheeting.

Granted, there are other variables which cause deterioration, but they are such that the effect is either temporary (as with dew, dirt, or frost), or their occurrence is unpredictable or unobservable. Thus, they are of limited utility in the determination of deterioration rates. For example, vandalism or accidents have an immediate and easily identifiable impact on the sheeting, but are better described as damage than deterioration. They provide little information on the reflective service life of the material.

Other causes of sheeting failure, such as manufacturing defects or improper sign fabrication techniques and materials, can result in obvious degradation such as color change, delamination, and clouding or cracking of the sheeting. Since these types of deterioration involve human error (difficult to observe and quantify) and are primarily mechanical in nature, little attention can effectively be focused on this area.

Finally, manufacturing changes over time that result in changes in the sheeting composition have the potential to affect the determination of a useful deterioration rate. That is, the current generation of retroreflective sheeting might be sufficiently different from that evaluated in the field over time that the identified rates might not apply.

## 6. Summary and Conclusions

- In the absence of performance standards which differentiate requirements based upon the specific application of a sign material, the current standards for retroreflective materials appear to serve well as acceptance standards. Testing is performed under simulated conditions and the results are primarily useful for comparisons and not to predict field results.

- Inconsistency is apparent among the retroreflective standards, manufacturers' claims, and measured brightness. Apparently, the sheeting currently manufactured is considerably brighter than the minimum values presented in the standards and manufacturers' literature. Unless new sheeting is photometrically tested before installation, the luminance after any period of deterioration is impossible to predict.

- Accelerated weathering tests appear to have limited applicability. Conversion of results is difficult.

- The durability and deterioration of retroreflective sheeting is a complex subject area. Natural deterioration is an interactive process of many variables and difficult to study. Some deterioration is transient and reversible. Further research is necessary and warranted in the area of natural deterioration of retroreflective sheeting.

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