Before widespread implementation of reward programs, further research must be performed. Tests must be conducted to define specific rates of change, when to use refreshers, the effects of socioeconomic status, reward ratios, maintenance levels, and other parameters.

ACKNOWLEDGMENTS

The Biological Research Support Grant Committee at the University of Alabama provided limited funding for this project. Appreciation is expressed to Dean McClure, Willie Peoples, Pauline D. Elkins, and David Layfield, and to many student volunteers whose efforts made this project possible.

Publication of this paper sponsored by Committee on Operator Education and Regulation.

Optimal and Minimal Luminance Characteristics for Retroreflective Highway Signs

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ABSTRACT

Presented in this paper are optimal and minimal sign luminance recommendations based on a review of available applied research. Optimal recommendations are based largely on peak luminance-legibility relationships. In the absence of other criteria, minimal recommendations are based on performance levels of 6 m/cm (20/23) for younger persons and 4.8 m/cm (20/29) for older persons. By using a computer sign legibility model, calculations were then made to determine the photometric characteristics of signing material required to obtain the values indicated.

One of the more significant questions facing any traffic agency is the optimum and replacement level for retroreflective signs. Caught up in this question are issues of safety, efficient movement of traffic, and costs. Because these are such important issues, a great number of investigations have been conducted to determine guidelines. The purpose of this paper is to review a selected portion of this research, and summarize the recommendations.

The review included experimental investigations pertaining to the legibility of a message on a sign constructed of retroreflective materials. Studies concerned with the relative merits of illuminated and retroreflective signs, as well as those dealing with nonlegibility issues (e.g., detection, color recognition, conspicuity, and comprehension), address a different set of problems and thus are beyond the scope of this review. Only applied research--whether on the road or in the laboratory--is covered. Purely basic research is not included.

As a first step in this work, a review of the literature was carried out. A total of 18 experimental studies were finally included. [See the original report for the detailed reviews of these studies (1).] Tabular reviews of each paper were prepared to facilitate a comparison of methods, findings, and recommendations. A synthesis of these data was prepared and will be presented in the next section.

A SYNTHESIS OF EXPERIMENTAL FINDINGS

A synthesis of the findings of the past research in terms of optimal and replacement (minimal) luminance values is provided in this section. The two most common sign types will be considered--a sign with a nonreflective black legend on a reflective light background, and a fully reflectorized sign with a white legend. In arriving at luminance recommendations, we will use geometric means to minimize the effects of extreme values.

The retroreflectance values required to achieve the desired luminance levels will be derived in the next section. The computations of the recommended luminance (and retroreflectance) values will be based on data collected under generally ideal conditions, such as signs placed in dark environments, sober observers, and clean signs. Therefore, in a later section, several variables that contribute to the argument for higher luminance values will be listed, along with some correction factors.

Optimal Luminance

Legibility is generally an inverted U-shaped function of luminance (2-4). Thus, determining optimal luminance for legibility purposes should be relatively easy: The optimum is at the crest of the function. Unfortunately, the issue is not that straightforward. The problem is that there exists a variety of inverted U-shaped functions, one each for all combinations of legend-background contrast, complexity of competing visual environment, age of the observer, and so forth. The state of the art is not advanced enough to deduce the parameters of all of these relevant inverted U functions. As a consequence, in reaching a synthesis regarding the optimum, we were forced to average over all relevant parameters. Furthermore, in a study by Allen and Straub, the crest of the function for black legend on light background was apparently not reached even with the highest tested luminance level (5). Nevertheless, the highest tested level in that study was used in averaging with optimal values from other studies that did find an asymptote or a decrease in legibility with the highest levels tested (4,6).

Black Legend on Light Background

The following studies have relevant luminance recommendations or findings for the situation where only the background luminance is appreciably greater than 0.

Luminance Value (cd/m^2)	Study Characteristics
343.0	Allen and Straub laboratory study (5)--an asymptote was apparently not reached even with the highest level tested
34.3	Allen et al. field study (7)--dark rural (used both 100% and 75% legend/background luminance contrast)
60.0	Dahlstedt field study (8)
206.0	Hind et al. laboratory study (6)--the data appear to asymptote at 206 cd/m^2)
55.0	Olson et al. laboratory study (4)--(recommended luminance: 10-100 cd/m^2)
24.0	Smyth laboratory study (9)

The geometric mean of these values is equal to approximately 75 cd/m^2. As a result, the recommended optimal luminance of a white, orange, or yellow background with a black legend is 75 cd/m^2.

Fully Reflectorized Signs

For fully reflectorized signs, as Olson et al. (4) pointed out, the optimal luminance of one component varies with the luminance level of the other component. As a consequence, for fully reflectorized signs, analagous computations were performed on the contrast findings.

Contrast Value	Study Characteristics
9.5:1	Forbes et al. laboratory study (10)--recommended range of 6-13:1
3.0:1	Forbes et al. field study (10)--light legends
7.5:1	Hills and Freeman laboratory study (11)--recommended minima of 8-10:1 for red, 7:1 for green, and 6-7:1 for blue
45.0:1	Olson et al. laboratory study (4)--recommended 30-60:1 for signs in the currently typical luminance range
12.9:1	Sivak et al. field study (12)--best performance at 10-15.8:1
21.0:1	Sivak and Olson field study (13)--best performance at 9-33:1

The geometric mean of these values is equal to approximately 12:1. As a result, the recommended optimal legend-background contrast for fully reflectorized signs is 12:1. For example, if the background luminance is 1 cd/m^2, the optimal luminance of the legend should be 12 cd/m^2.

Replacement Luminance

"Replacement (minimal) luminance" implies the point at which the sign is failing to fulfill its nighttime function. From many points of view, replacement luminance is more important than optimal luminance. There is, unfortunately, no consensus concerning what the minimum function of a sign is. If, for example, there was some agreement concerning minimum legibility distance, then determining the luminance levels required to achieve it would be relatively simple. Lacking such guidelines, luminance-legibility relationships might be expected to be found that would suggest a cut-off point. If, for example, there was a luminance-contrast level below which legibility dropped off very rapidly, this might then serve as an obvious minimum level. However, there does not appear to be such a discontinuity in the available data.

No criteria now exist for establishing minimal sign luminance levels that are likely to meet with wide acceptance. In the absence of such criteria, the replacement level recommendations presented here are based on the following legibility levels: 6 m/cm (50 ft/in.) of letter height for studies that use exclusively younger observers, younger and older observers, or if the observers' age was not reported; and 4.8 m/cm (40 ft/in.) of letter height for studies that use exclusively older observers. The rationale for the selection of these criteria is as follows:

1. 6 m/cm corresponds to visual acuity of approximately 20/23 (14). This value is close to the usually found average visual acuity for younger and middle-aged persons. [In one of the most comprehensive studies on this topic, Burg (15) found the average visual acuity of 16,137 persons between 16 and 64 years of age to be 20/20.] Furthermore, 6 m/cm is frequently used as a legibility criterion.

2. 4.8 m/cm corresponds to visual acuity of approximately 20/29. This value is close to 20/26, the average visual acuity obtained by Burg (15) for a sample of 1,301 persons between 65 and 92 years of age. [By combining the 16,137 persons between 16 and 64 years of age with the 1,301 persons between 65 and 92 years of age, Burg found the average visual acuity to be approximately the same as the average visual acuity for the subsample of persons between 16 and 64 years of age. (This is a consequence of the relatively few older persons who enter the averaging process for the combined sample.) Therefore, the same criterion was used for studies using

either exclusively younger subjects, or younger and older subjects.]

The following are findings relevant to the issue of replacement luminance (values shown are for the lighter component, whether legend or background):

Replacement Value (cd/m^2)	Study Characteristics
3.00	Allen and Straub (5); white and black backgrounds; estimated from their Figure 7 for Series C letters; criterion: mean at 6 m/cm (young observers)
2.00	Allen (16); black background; estimated from his Figure 8; criterion: mean at 6 m/cm (younger and older subjects)
6.90	Allen et al. (7); white and black backgrounds; estimated from their Figure 11; criterion: mean at 4.8 m/cm (older observers)
2.00	Hills and Freeman (11); green, blue, and red backgrounds (of up to about .3 cd/m^2); estimated and averaged from their Figures 6 through 8; criterion: mean at 6 m/cm (observer age unspecified)
1.30	Olson et al. (4); green and red backgrounds (of up to about .4 cd/m^2), as well as white, yellow, and orange backgrounds; estimated and averaged from their Figures 1-29 through 1-33 and 1-35; criterion: 50% correct at 4.8 m/cm (older observers)
0.93	Richardson (17); various backgrounds; criterion: mean at 6 m/cm (young observers)
4.60	Smyth (9); white and black backgrounds; criterion: mean at 6 m/cm (observer age unspecified)

The geometric mean of these values is equal to approximately 2.4 cd/m^2. As a result, the recommended replacement luminance of the lighter component is 2.4 cd/m^2. This recommendation applies to light backgrounds (white, yellow, and orange) with black legends, and to white legends with dark (green, blue, red, or brown) backgrounds having background luminance of up to 0.4 cd/m^2. [As the luminance of the background increases above 0.4 cd/m^2, the replacement luminance of the legend is dependent on the particular level of the background luminance (4)].

RETROREFLECTANCE CONSIDERATIONS

The technical term for retroreflectance is "coefficient of retroreflection," symbolized by R' (ASTM E 808, Standard Practice for Describing Retroreflection). In metric form, R' is defined as $cd/lux/m^2$. Knowing the luminance levels required to achieve a given objective, it is desirable to determine the retroreflectance required. This could be done in several ways. One is to use existing data, such as that of Woltman and Youngblood (17), and extrapolate from their measurements. In this case, calculations of the retroreflectance values were made by using a computerized nighttime sign legibility model. This program was developed by the University of Michigan Transportation Research Institute (UMTRI) for the 3M Company (4). The model accepts a great number of input parameters (e.g., sign location, retroreflective materials, color, headlamps, road geometry, background characteristics, and viewing distance) and predicts legibility distance. For this task, the input values were optimal and replacement luminance values derived earlier; candela values derived from U.S.- and European-type low-beam headlighting systems; an assumed legibility distance of 183 m (600 ft); and four sign locations designated as follows: right shoulder [2.4 m (8 ft) up, 2.4 m (8 ft) right], left shoulder [2.4 m (8 ft) up, 6 m (20 ft) left], shoulder guide [2.4 m (8 ft) up, 10.7 m (35 ft) right], and overhead [6 m (20 ft) up, 0 m (0 ft) right]. (The right shoulder and shoulder guide locations were measured from the right edge of the lane, the left shoulder from the left edge of the lane, and the overhead from the center of the lane.)

The calculated optimal and replacement retroreflectance values for signs placed in dark surrounds are given in Tables 1 and 2. The optimal values in Tables 1 and 2 apply to signs having light (white, yellow, and orange) backgrounds with black legends. For fully reflectorized signs, the optimal retroreflectance of one component (legend or background) depends on the given retroreflectance of the other component. For these signs, the optimal contrast value of 12:1 derived earlier can be used to obtain an approximation to the optimal retroreflectance of one component from the known retroreflectance of the other component. For example, if the background retroreflectance is set at 2 $cd/lux/m^2$, the corresponding optimal retroreflectance of the legend is 24 $cd/lux/m^2$.

The replacement values in Tables 1 and 2 apply to signs placed in dark surrounds. These values apply to light backgrounds (white, yellow, and orange) with black legends and to legends of fully reflectorized signs having backgrounds of up to 0.4 cd/m^2. (As the luminance of the background increases above 0.4 cd/m^2, the replacement luminance of the legend is dependent on the particular level of the background luminance (4).

The replacement luminance values derived earlier were based on mean data, which are likely to be in the neighborhood of the 50th percentile, and in one instance, on the 50 percentile (4). However, 75th and 85th percentile estimates would also be desirable. Consequently, Tables 1 and 2 list the corresponding sign luminance and retroreflectance values for the 50th percentile performance, as well as for 75th and 85th percentiles, which were obtained from the 50th percentile values by using factors of 3 and 7. These factors were estimated and averaged from Olson et al. (4) by using their data for signs with green and red backgrounds of up to

TABLE 1 Optimal and Replacement Coefficients of Retroreflection ($cd/lux/m^2$) when Using U.S.-Type Low-Beam Headlighting Systems[a]

		Sign Location			
Level	Sign Luminance (cd/m^2)	Left Shoulder	Overhead	Right Shoulder	Shoulder Guide
Optimal	75	2,806	3,547	736	856
Replacement percentile					
85th	16.8	630	798	168	189
75th	7.2	270	342	72	81
50th	2.4	90	114	24	27

[a]The optimal values apply to white, yellow, and orange backgrounds of signs with black legends. (For fully reflectorized signs, the optimal legend-to-background contrast is 12:1.) The replacement values apply to white, yellow, and orange backgrounds of signs with black legends, and to legends of fully reflectorized signs with backgrounds of up to 0.4 cd/m^2. The listed optimal and replacement values apply to generally ideal conditions; for possible correction factors, see Table 3.

TABLE 2 Optimal and Replacement Coefficients of Retroreflection (cd/lux/m²) when Using European-Type Low-Beam Headlighting Systems[a]

Level	Sign Luminance (cd/m²)	Sign Location: Left Shoulder	Overhead	Right Shoulder	Shoulder Guide
Optimal	75	4,644	7,252	2,436	1,113
Replacement percentile					
85th	16.8	1,043	1,624	546	252
75th	7.2	447	696	234	108
50th	2.4	149	232	78	36

[a]The optimal values apply to white, yellow, and orange backgrounds of signs with black legends. (For fully reflectorized signs the optimal legend to background contrast is 12:1.) The replacement values apply to white, yellow, and orange backgrounds of signs with black legends, and to legends of fully reflectorized signs with backgrounds of up to 0.4 cd/m². The listed optimal and replacement values apply to generally ideal conditions; for possible correction factors see Table 3.

0.4 cd/m² and for signs with white, yellow, and orange backgrounds.

CONTRIBUTING VARIABLES

The derivations of the optimal and replacement luminances presented earlier were based on data collected with sober subjects under low-luminance surround conditions. As a result, the derived values are probably conservative. Table 3 gives several variables that contribute to the argument for higher luminance values, along with some corresponding correction factors. (The listed factors were derived from the cited references.)

TABLE 3 Contributing Variables and Correction Factors

Contributing Variable	Correction Factors: Optimal Value	Replacement Value
High-luminance surround and environmental glare *(7)*	20x	20x
Driver age *(12)*	–[a]	–[b]
Truck drivers: observation angle *(19)*	2-5x	2-5x
Alcohol intoxication *(20)*	–[a]	–[a]
Dirty signs *(21)*	1.2-20x	1.2-20x
Dirty headlamps *(22)*	<1-10x	<1-10x
Misaligned headlamps *(23)*	–[a]	–[a]

[a]Data unknown.
[b]The effect of driver age on replacement values can be considerable; however, it is highly specific to the set of conditions used. In addition, older drivers have shorter legibility distances and therefore have less time in which to act on the information in the sign message.

CONCLUSIONS

In this study applied research on sign legibility was reviewed to obtain information on optimal and replacement luminances of retroreflective traffic signs.

The legibility data reviewed suggest that for signs that have light (white, yellow, and orange) backgrounds with black legends placed in low luminance surrounds, the optimal luminance of the background is approximately 75 cd/m². For fully reflectorized signs, the optimal luminance of one component depends on the given luminance of the other component. The data suggest that for these signs the optimal legend to background contrast is about 12:1.

By assuming legibility criteria of 6 m/cm of letter height for younger subjects and 4.8 m/cm for older subjects, the reviewed legibility data suggest that the replacement luminance value is 2.4 cd/m². This applies to light legends with dark (green, blue, red, and brown) backgrounds of up to 0.4 cd/m², and to light (white, yellow, and orange) backgrounds with black legends. By using these optimal and replacement luminance values, optimal and replacement retroreflectance values for commonly used colors of retroreflective materials were derived in Tables 1 and 2 for signs in four different locations, illuminated by U.S. or European low-beam headlighting systems. The present recommendations were derived by averaging a set of values from studies run under generally favorable conditions. As a result, several variables that contribute to the argument for higher luminance values were listed in Table 3, along with some correction factors.

This review dealt only with legibility issues. However, luminance contributes to other functional properties of traffic signs, including conspicuity and ease of color recognition. Thus, the compromises that led to the legibility-based recommendations must be supplemented with compromises based on other criteria applicable to traffic signs. An issue of consequence is how the minimal recommendations can be used by traffic agencies in their replacement programs. This is a difficult question because although equipment for measuring retroreflectance in the field exists, it is not practical for regular measurements on large numbers of signs. Until a more convenient means can be developed, the simplest way is probably to rely on time-related performance data, either from manufacturers or from the agency's own experience.

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Publication of this paper sponsored by Committee on Visibility.

Freeway Lighting and Traffic Safety—A Long-Term Investigation

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ABSTRACT

The objective of this study was to assess the effectiveness of freeway lighting. To achieve this, a case study on traffic accident characteristics was conducted that utilized a suburban freeway area west of Frankfurt, Federal Republic of Germany, between 1972 and 1981. The study revealed that (a) the effects of lighting on suburban freeway accident rates was positive--there was a reduction in accidents, and (b) these positive results of continuous freeway lighting were lost in the case of partial lighting, especially after switching off lights at night between 10:00 p.m. and 5:30 a.m. for the purpose of saving energy.