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Contents

Foreword

The papers included in this Record were presented at the Symposium on Visibility for Roadways, Airways, and Seaways held during July 1990 in Washington, D.C. The symposium was the tenth in a series sponsored by the TRB Committee on Visibility.

The objective of the symposium was to present recent research results and information from ongoing research and development on a variety of lighting and visibility topics, from measurement and characterization to human performance and safety benefits.

Unique to this symposium was the introduction of research findings related to minimum standards for retroreflectivity of traffic signs and pavement markings. The outcome of this research may be the development of minimum maintained levels of retroreflectivity for traffic signs and markings.

Also presented at the conference were papers related to visual aids to navigation for a ship's position and visibility criteria applicable to guidance of traffic in situations in which ground fog becomes a serious hazard.

The TRB Committee on Visibility encourages comments on this and other visibility publications and suggestions for future symposium topics.

New Jersey Guide-Sign Survey

ARTHUR W. ROBERTS

As part of a study to review difficulties of drivers in viewing large guide signs, or "interferences," on state highways in New Jersey, a survey from a fast-moving automobile was performed. The survey covered more than 1,000 approaches to interchange exits in the 2,000-mi New Jersey system. More than 580 motorist view interferences were discovered through visual observations. The method was verified to be 94 percent accurate using a videotape method and a legibility formula with a sample of approaches. Sign view blockage by difficult- and expensive-to-modify highway features and furniture represented 35 percent of the interferences. Computer graphic interchange modeling at an earlier design stage is recommended to help avoid view blockages in the future.

At interchanges, guide signing plays an important part in the overall effectiveness and efficiency of the operation of the interchange. Although guide signing cannot totally make up for unexpected interchange design, it can serve to lessen confusion and smooth traffic flow. This leads to more efficient and sometimes safer operation of interchanges and the road system as a whole.

At many interchanges, motorists are confronted with identification and reading difficulties concerning signs that have adequate target value, legend size, and legibility. However, because of the physical design of interchanges or approaches to interchanges, the placement of signs, or the placement of other fixed physical objects, absolute and unchanging interferences with the visibility of the signs to approaching motorists are created.

Because sign visibility interferences reduce motorist identification and reading time, sometimes considerably, erratic vehicle movements, speed variances, and other safety problems can result.

The capital and maintenance investments in large guide signs is significant. A 200 ft^2 ground-mounted sign with footings typically costs $16,000, and a sign bridge can cost more than $150,000. The return on investment is reduced when signs cannot perform their real functions. The design of interchanges is involved in the interference of sign views. Interchanges in New Jersey cost tens of millions of dollars. Landscaping and maintenance add to the cost.

It should be understood that purchasing rights-of-way, removing rock formations, and linking with existing roads create practical problems that sometimes constrain optimal sign placement. It also appears that traffic engineers do not have a practical way to obtain a driver's view of tentative plans.

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LARGER STUDY ACTIVITIES

The subject of this report, an interchange guide-sign survey of view interferences from a moving automobile, was part of a larger study. The larger study also involved the use of a more detailed videotape review of a limited number of sites and the demonstration of four-dimensional computer graphic modeling of interchanges to integrate sign placements and physical design.

The videotapes of approaches were analyzed using a legibility distance formula reported by King (*1*), which includes consideration for the number of information elements on a sign. The accuracy of the observations from the automobile were checked by the videotape method at 19 interchange approaches. Ninety-four percent of the observations of permanent sign blockages was accurate, based on the limited sample.

The videotape method can be useful for performing accurate sign sight distance measurements and making percentage statements of sign interference severity. Observations from a moving automobile, however, are faster, less expensive, and adaptable to large-scale surveys of thousands of signs normally found in large highway systems.

SCOPE AND PROCEDURE

An interchange is defined as having one or more exits to a grade-separated route. An approach is a section of roadway that ends with an interchange exit, exits, or upstream exit decision point.

The number of interchanges in New Jersey was estimated to be 693. On the state system, interchanges have single, double, triple, and quadruple approaches. A random sample produced an estimate of 10 percent single and 90 percent double approach interchanges, which yields 1,317 approaches. The total number of approaches surveyed was 1,012, or about 75 percent.

The survey was carried out in daylight during the summer and fall of 1987 in a 1986 Dodge Aries to determine where the driver's view of a guide sign was less than maximum readability. The earliest point at which an interference was noted was established where the observer could clearly notice and read the entire message on the sign at a point downstream of where it should have been legible. An assumption was made that the smallest legends used were adequate for current standards. Because some signs were probably inadequate for current standards, the percentage of interferences found might be conservative. However, it must be noted that the observers were young people with good uncorrected vision, which would tend to make their judgment liberal.

The purpose of the larger project was limited to sign placement and design method improvements. This survey was not intended to substitute in any way as a traffic engineering operation. Approaches involving isolated sites, tolls, and state border crossings were not surveyed. The value, ambiguity, or lack of transmissivity of the message was not evaluated. The effects of blockage by moving or parked vehicles and the views from other lanes were not surveyed. Undoubtedly many more interferences would have been found had these factors been taken into account. The purpose here is to summarize an extensive preliminary investigation of sign view interferences by using a reasonably accurate, low cost, and fast methodology.

The following sign types were surveyed (Figure 1):

1. Advance,
2. Supplemental advance,
3. Exit direction,
4. Gore, and
5. Pull through, including both ground-mounted and overhead signs.

RESULTS

Of the 1,012 approaches surveyed, 583 interferences of varying severity were noticed that left the observers with less than maximum viewability within their readable range.

The interferences are classified and distributed by number and percentage in Table 1. The classification can be simplified into the following four main categories of interference, which do not include damaged or deteriorated signs:

1. Sign view blockage, which represents 97 percent of the cases observed. The term means that the approaching motorist's view is blocked by some fixed object. The method is accurate for this type of interference.
2. Complex environment, which represents only 1 percent of the cases observed. The term means that the environment or the construction of the sign is such that it is easily overlooked (Figure 2). Further definition of this type of interference appears to be needed.
3. Ambiguous meaning, which represents only 1 percent of the cases. The term means that the sign is placed on a parallel road in such a way that the driver may be uncertain whether or not an upstream decision was correct. The identification of this category may require special training.
4. Information overload, which was found at only one interchange approach. It must be noted that this survey method may be inadequate for this category.

Because the sign view blockage category represents 97 percent of the cases observed, a breakdown of the types and percentages is warranted and is shown in Table 1.

Trees accounted for 53 percent of the blockages observed (Figure 3). Poles accounted for 5 percent, curves and crests for 20 percent. Other signs accounted for 6 percent, and bridge spans, abutments, parapets, and piers accounted for 13 percent (Figures 4, 5, and 6).

Some types of interferences were not found, including the following:

- Visual cone: No signs were found to be outside the driver's 20–degree cone of vision until the end of the approach.
- Unexpected location: No signs were observed to be located in a spot that is unexpected by the drivers, thus causing a noticeable decrease in the readable range.

Signs that were found to have one or more interferences are as follows:

Type of Sign	*Percent of interferences*
Advance	48
Exit direction	36
Gore	11
Supplemental advance	10
Pull through	3
Miscellaneous	2

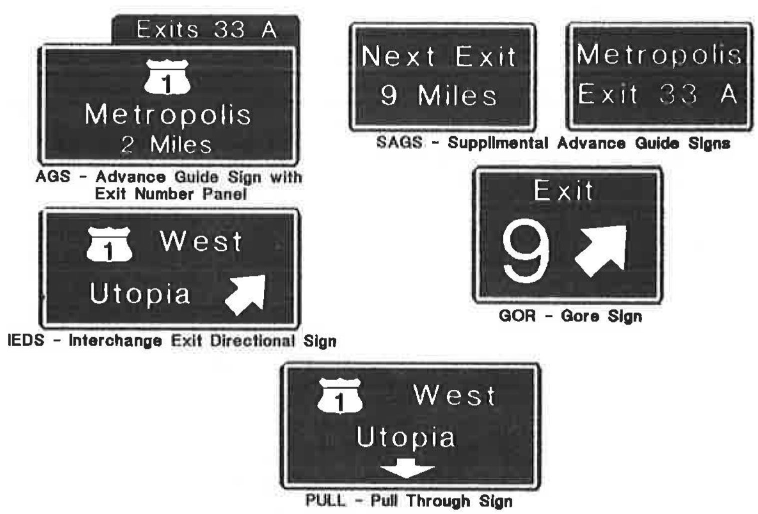

FIGURE 1 Sign types.

TABLE 1 DIRECTIONAL GUIDE-SIGN VIEW INTERFERENCES

Reason for view Interference	Frequency	Percentage of Total
Trees	309	53
Curves	86	15
Crests	32	5
Bridge spans	40	7
Telephone poles	32	5
Signs	39	6
Bridge abutments	11	2
Bridge parapets	10	2
Bridge piers	10	2
Complex environments	6	1
Ambiguous meaning: due to parallel roads	4	1
Buildings, information overloads, signs down, signs broken	4	1
	583	100

FIGURE 2 Complex environment.

FIGURE 3 Tree blockage.

FIGURE 4 Bridge span blockage.

FIGURE 5 Bridge pier blockage.

FIGURE 6 Parallel roads.

DISCUSSION OF RESULTS

The view blockage of highway signs has been reported before, recently by Hahn et al. (*2*), who noted, "The target value of many large guide signs is limited by high surrounding brightness, and by blockage by other highway features."

It was found that a little more than half of the blockages were caused by trees. The maintenance of landscaping is normally an annual event if sufficient funds are available. Trees and shrubs are relatively inexpensive to modify. Apparently, when they were originally located in the design phase, the impact of this growth process was often not foreseen. They can be cut back or removed to correct the interferences at relatively low cost.

Poles are a bothersome interference, but the interference appears to be minor in most cases. Small signs blocking large signs can be moved inexpensively. However, large signs, curves, embankments, walls, spans, parapets, and piers represent an estimated 35 percent of the problem. The correction of these interferences would require relocation of large signs, new road alignments, bridge replacement, or the reconstruction of other features, involving large capital investments.

It is recommended that more attention be placed on testing scale models at an early design stage, involving both signs and features before the building of new interchanges and alignments.

Three-dimensional dynamic computer graphics can provide a practical way to test the driver's view at an early stage with a more effective input and review of traffic engineers (*3*).

The technical means for traffic engineering input with optimal sign placement for each unique interchange has been crude in comparison with the means that are available today.

The information for this presentation is primarily taken from a report by Roberts and Black (*4*). The methodology in this survey may be used in other states to quickly assess the approximate number and location of sign view interferences without the need for specialized equipment. A rough, subjective assessment of the severity of the interference, such as a three-point scale, should also be used.

ACKNOWLEDGMENTS

The author gratefully acknowledges the data collection and survey organization performed by Thomas Black and the videotape survey work by Edward Pennell, which formed the numerical basis for this presentation.

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Traffic Signal Visibility: A Preliminary Standard for Round Signal Indications Derived from Scientific Research

MICHAEL S. JANOFF

The objective of this paper is to derive a preliminary traffic signal standard for round signals based on the extensive, worldwide scientific research addressing the visibility and conspicuity requirements of traffic signals. The literature was reviewed, analyzed, summarized, and critiqued by a group of experts in visibility and related sciences, and a preliminary standard was derived from these analyses. The preliminary standard includes specifications for color, peak daytime intensity, intensity distribution, nighttime intensity and dimming, use of backplates, effects of depreciation and phantom limits for both 8-in. (200-mm) and 12-in. (300-mm) red, green, and yellow signals.

It is imperative that traffic signals capture the attention of drivers and pedestrians, including those who are elderly, color deficient, or distracted, and those who are not expecting a traffic signal. This must be accomplished under widely varying conditions, including bright sunshine, adverse weather, at night, with noisy or complex backgrounds, in rural areas, in high-speed traffic, at or between intersections, and at many other types of locations. Traffic signals should not be overly bright, however, because this could result in excessive glare and thus reduce the visibility of drivers, and could also result in excessive power costs.

To capture the attention of motorists, a traffic signal must be both visible and conspicuous. The visibility of a signal is normally defined by detection or probability of detection, and the probability of detecting a light signal depends on its intensity. The detectability of a signal is understood to be the property of the signal that enables its presence to be detected by an average observer under favorable circumstances with regard to attention, atmospheric conditions, and psychological or physiological influences when the observer has no other task to perform. Detection usually refers to threshold detection.

The conspicuity of a signal is the property that allows it to stand out with respect to other similar but irrelevant signals. Conspicuity is not the same as detection and has little to do with threshold values. Conspicuity refers to properties of the signal and the surroundings, and includes properties of distribution of attention of the observer. The intensity requirements for conspicuity are far higher than those for detection alone—often 100 to 1,000 times higher. Any traffic signal standard must therefore account for both the visibility and conspicuity requirements of signal lights; intensity levels must be sufficiently high to satisfy both concepts.

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STANDARDS AND SPECIFICATIONS: DEFINITIONS AND BASES

A standard indicates the minimum performance required of a system at the end of its useful life, whereas a specification, or purchase specification, is for procurement of new systems and only indicates the performance of a system when it is new.

Standards and specifications can be based on scientific research, empirical descriptions of systems that have functioned well in the past, ad hoc observations of existing systems and their performance, practical experience, current practice, consensus of experts, and other considerations.

OBJECTIVE AND EVALUATION

The objective of this paper is to derive a preliminary traffic signal standard based on the extensive, worldwide, scientific research addressing the visibility and conspicuity of traffic signals, and to more precisely and scientifically relate traffic signal standards to the needs of drivers under typical driving conditions.

Only the preliminary standard for round signals is addressed here; standards for symbols such as arrows, pedestrian controls, and so on are addressed elsewhere (*1*). In addition, bases other than scientific research are not considered.

To meet this objective, results of scientific research from the United States, Europe, Australia, and other areas were obtained, reviewed, summarized, and critiqued by a group of experts in visibility, electrical engineering, traffic engineering, human factors engineering, psychology, and optics.

To determine the level of support for each part of the ideal standard and derive the preliminary standard, a literature search, a review of abstracts to identify the scientific research most related to the project objectives, a critical evaluation of the most important publications, and an analysis to identify the necessary parts of an ideal traffic signal standard were conducted. A complete description of this evaluation is found elsewhere (*1*).

SCIENTIFIC RESEARCH BASES OF TRAFFIC SIGNAL STANDARDS

The scientific research bases of a traffic signal standard for round signals, including development of a preliminary traffic signal standard for round signals, are described in this section.

Color of Signals

On the basis of nearly universal acceptance of the Commission Internationale de l'Eclairage (CIE) (International Commission on Illumination) colors—even by other forms of transportation in the United States—those colors appear to be preferred. The support of these colors is extensive laboratory research [see for example the bibliography in CIE Publication 48 (*2*)]. The choice of colors also includes the needs of the aged and color-vision deficient. The tristimulus equations defining the red, green, yellow, and white regions, and the coordinates of the corner boundary points are defined in Table 1. A more complete description of these equations and their bases is provided elsewhere (*2*).

Daytime Intensity

Based on considerable analytic, laboratory, and controlled field research the peak (minimum) intensity of a red 8-in. traffic signal should be 200 cd. Such a value should suffice for all sky luminances up to 10,000 cd/m², observation distances up to 100 m, and vehicle speeds up to 80 km/hr. This value is a maintained one, and depreciation caused by dirt and aging of lamps must be taken into consideration. These results are based on analytic, laboratory, and controlled field experiments performed by Cole, Boisson, Adrian, Jainski, Fisher, and Rutley (*3–10*).

The major result of this research was the development by Cole of a formula and nomogram (Figure 1) that defines optimum peak red signal intensity as a function of distance to signal and background luminance (*5*). The formula is

$$I(d) = 2d^2 \times Lb \times 10^{-6} \qquad (1)$$

where

d = distance to signal (m),
Lb = sky luminance (cd/m²), and
$I(d)$ = intensity at distance d (cd).

For roads that carry high-speed traffic (up to 100 km/hr) and distances up to 240 m, analytic research by Hulsher, derived from the results of Cole and others, has indicated that a red signal requires a peak intensity of 895 cd (*11*). This is a narrow-beam 12-in. signal; there is no research to support specifications for a wide-beam 12-in. signal. Hulsher derived a formula that extends Cole's.

$$I = 1.03\,[(d^2 + h^2)D]^{0.667} \qquad (2)$$

where

d = distance to the signal along the line of sight (m),
h = height of the signal (m),
D = stopping distance at the speed of traffic (m), and
I = intensity (cd).

For green signals Fisher and Cole have indicated that, based on previous laboratory and controlled field research by Adrian, Rutley, Jainski, and Fisher, the ratio of green to red intensity should be 1.33:1. They also suggest that, based on the previous research of Rutley and Jainski, the ratio of yellow to red intensity should be 3:1 (*3,7–10*).

Table 2 summarizes the peak intensity requirements of red, green, and yellow traffic signals for normal-speed roads (8 in.) and high-speed roads (12 in.). This table excludes the use

TABLE 1 COLORS OF TRAFFIC SIGNALS

A. Boundary Equations

COLOR	BOUNDARY	EQUATION
Red	Red	y = 0.290
	Purple	y = 0.990 - x
	Yellow	y = 0.320
Yellow	Red	y = 0.382
	White	y = 0.790 - 0.667x
	Green	y = x - 0.120
Green	Yellow	y = 0.726 - 0.726x
	White	x = 0.625y - 0.041
	Blue	y = 0.390 - 0.171x
White	Yellow	x = 0.440
	Purple	y = 0.047 + 0.762x
	Blue	x = 0.285
	Green	y = 0.150 + 0.640x

B. Coordinates of Boundary Corners

COLOR	POINT NUMBER 1		2		3		4	
	x	y	x	y	x	y	x	y
RED	0.710	0.290	0.700	0.290	0.670	0.320	0.680	0.320
YELLOW	0.618	0.382	0.612	0.382	0.546	0.426	0.560	0.440
GREEN	0.008	0.720	0.284	0.520	0.183	0.359	0.028	0.385
WHITE	0.440	0.382	0.285	0.264	0.285	0.332	0.440	0.432

Source: Reference 15

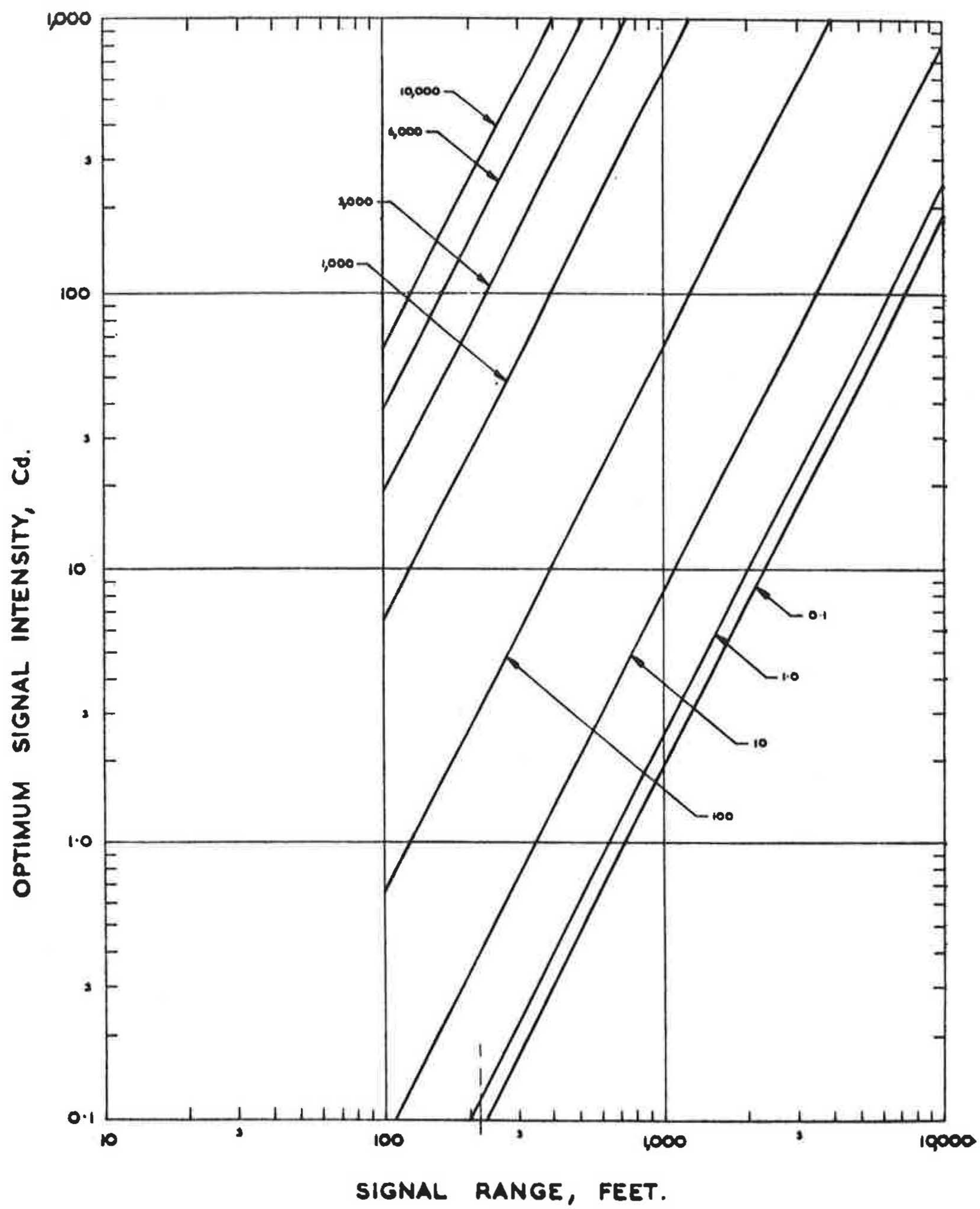

FIGURE 1 Nomogram showing optimum intensity for red road traffic signal as function of maximum signalling range for various background luminances in foot lamberts (*6*).

TABLE 2 PEAK DAYTIME INTENSITY REQUIREMENTS

SIGNAL SIZE	PEAK INTENSITY REQUIREMENT (cd) (MAINTAINED; NO BACKPLATE) RED	GREEN	YELLOW
8"	200	265	600
12"	895	1190	2685

of a backplate and ignores depreciation effects, both of which will be discussed subsequently. Although signal size is included in Table 2 (i.e., 8 in. and 12 in.), laboratory research by Cole has indicated that signal size is not important; only intensity affects visibility (*6*). That is, traffic signals are point sources and not area sources, and required intensities can be obtained by means other than changing signal size (e.g., use higher intensity sources in 8-in. signals).

Backplates

For 8-in. signals Cole (*12*) has shown through laboratory research that the use of a backplate reduces the peak intensity requirement by about 25 percent at distances of about 100 m (sky luminance of 10,000 cd/m² and speed of 80 km/hr), but has little effect at longer distances unless the dimensions of the backplate are excessive. Fisher (*13*) and Fisher and Cole (*8*) derived a 40 percent intensity reduction for 8-in. signals at distances of 100 m and greater reductions at shorter distances—up to 90 percent at distances less than about 25 m.

Hulsher (*11*), in analytic computations based on Cole's work, has shown that a 12-in. signal (speed of 100 km/hr, sky luminance of 10,000 cd/m^2, and distance of 240 m) with a backplate requires about one-third less intensity—dropping the intensity requirement of a 12-in. red signal to 600 cd. However, Fisher and Cole stated that only an 11 percent reduction in intensity is possible (from 895 to 800 cd) because of the smaller effect of the backplate at these longer distances.

Under a conservative approach the peak intensity requirement for 8-in. red signals would drop to 150 cd, and the peak intensity requirement for 12-in. red signals would drop to 800 cd. Green and yellow intensities can easily be derived using the appropriate ratios. These are maintained values and do not include the effect of depreciation, which will be discussed in the following section. A more robust approach would drop the 8-in. red peak intensity to 120 cd and the red 12-in. to 600 cd.

Cole and Jainski have performed controlled field experiments, and Fisher and Cole have re-analyzed the data to derive a proposed size of the backplate of three times the diameter of the 200-mm (8-in.) signal. The color of the screen should maximize contrast between the screen and the sky (i.e., be mat black) (*8*).

Fisher and Cole have derived a nomogram that illustrates how much the intensity can be reduced if a backplate of different dimensions is used. From this nomogram specific reductions in required signal intensity can be derived for different backplate dimensions and distances from the signal; hence, some indication of effectiveness of such backplates can be derived.

However, the (minimum) background levels of luminance or (maximum) distances at which such backplates are still effective are not specified. Because of the relatively low additional cost of a backplate and the distinct benefits resulting from the lower peak intensities, including energy savings, lower nighttime glare, and reduced distribution requirements (to be discussed subsequently), such backplates appear to be preferred (*8*).

Depreciation

Hulsher (*14*), in an analytic and field measurement study, has shown that signals that are cleaned every 6 months require 20 percent additional peak intensity to ensure that the values in Table 2 are met at all times. CIE recommends that a loss of 25 percent be included to account for depreciation (a 33 percent increase). The recommendation is somewhat higher than Hulsher's, but probably is reasonable to account for cleaning periods longer than 6 months (*15*).

For a conservative approach, combining the use of a backplate with a depreciation factor of 33 percent yields a red peak intensity for new signals (as manufactured) with backplates of 200 cd (200 × 0.75 × 1.33, rounded to the nearest 10 cd) for 8-in. signals and about 1,060 cd for 12-in. red signals (895 × 0.89 × 1.33). Again, green and yellow intensities can be derived from the proper ratios, as can the respective values, using more robust approaches.

Daytime Distribution

Two studies have been performed: an analytic study by Cole, in which the signal was considered to be directly in the line of sight of the observer, and a controlled field experiment by Fisher, in which the signal was placed eccentric to the line of sight. Fisher's research is an extension of Cole's (*13,16*). Fisher's research yielded a formula for an optimum distribution for 8-in. signals. The formula can be used to extend the nomogram of Cole to include signals eccentric to the line of sight.

The formula for computing intensity at different eccentricities is

$$I(d,a) = 2K \times d^2 \times Lb \times 10^{-6} \quad (3)$$

where

d = distance to signal (m),
Lb = sky luminance (cd/m^2),
a = angle of eccentricity (degrees), and
$K = (a/3)^{1.33}$.

$$a = a(v) + a(h)$$

where

$a(v)$ = vertical eccentricity of signal (degrees), and
$a(h)$ = horizontal eccentricity of signal (degrees).

In addition, $a(v)$ and $a(h)$ are dependent on the height of the signal and the driver's eye height (*14*).

The optimum distribution for 8-in. signals derived by Fisher is presented in Table 3; the use of a backplate is assumed. Figure 2 illustrates the distribution. Fisher has shown, in controlled field research, that the use of such a backplate permits the distribution of intensity to be more concentrated in the center of the beam (*13*). Table 3 also includes, for comparison purposes, an approximation of the optimum distribution when a backplate is not used. This later was also derived from the results of Fisher (*13*).

For 12-in. signals, Fisher and Cole (*8*) recommended using the same distribution as for the 8-in. signal but increasing the peak intensity for the central beam (horizontal angles less than 5 degrees and vertical angles less than 3 degrees) by a factor of 4. Hulsher (*14*), in more rigorous analytic research,

TABLE 3 OPTIMUM DISTRIBUTION FOR 8-IN. TRAFFIC SIGNALS

ANGLE (degrees)		INTENSITY (% of peak)	
HORIZONTAL	VERTICAL	BACKPLATE	NO BACKPLATE
0 - 5	0 - 3	100	100
5 - 10	3 - 5	50	80
10 - 20	5 - 10	12.5	40
20 - 30	10 - 20	7.5	30

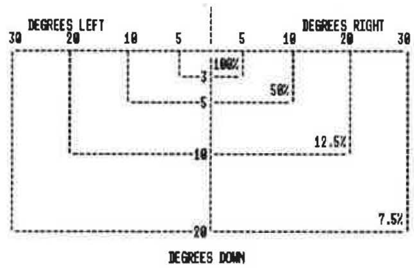

FIGURE 2 Optimum intensity distribution (percent of peak intensity) (*13*).

has extended the work of Cole to include 12-in. signals. The results are summarized in Table 4.

No research has been conducted to investigate whether different color signals require different intensity distributions.

Nighttime Intensity

Two separate issues must be addressed: (a) minimum intensities required at night (i.e., how much the signals can be dimmed without causing a decrease in visibility) and (b) maximum intensities that should be used at night (i.e., when signals should be dimmed because of excessive glare, and by how much).

Cole has suggested that based on his laboratory research, the optimum found for daytime red intensities will suffice at night in an urban environment (*6*). However, Cole did not investigate either issue described above.

Concerning the minimum levels of intensity, Freedman, in a series of laboratory, controlled field, and observational studies, found that signal intensities could be reduced to the values presented in Table 5 without adversely affecting nighttime visibility. Normal drivers, aged drivers, and color-vision deficient drivers were all considered in these results (*17*).

A further implication of these results is that signals can probably be reduced to the values in the first row of Table 5

TABLE 4 OPTIMUM DISTRIBUTION FOR 12-IN. TRAFFIC SIGNALS

ANGLE (degrees)		INTENSITY (% of peak)	
HORIZONTAL	VERTICAL	BACKPLATE	NO BACKPLATE
0 - 2.5	0 - 1.5	100	100
2.5 - 4	1.5 - 2	67	95
4 - 5	2 - 3	33	90
5 - 7.5	3 - 4	25	80
7.5 - 10	4 - 5	17	60
10 - 15	5 - 10	8	30

TABLE 5 RECOMMENDED MINIMUM INTENSITY LEVELS FOR FULLY DIMMED SIGNALS

SIGNAL SIZE	RED	COLOR YELLOW	GREEN
8"	50	220	95
12"(1)	120	555	240

(1) wide angle in Reference Number 18
Note: All values rounded to nearest 5 candelas

(i.e., the 8-in. values) without adversely affecting visibility (because, as discussed previously, signal size was found to be unimportant with respect to visibility; only intensity defines visibility). This does not, however, imply that all signals should be reduced in intensity at night. The traffic, geometry, and background complexity all affect this decision. Guidelines have been developed by Freedman for determining the surrounding area where dimming is advisable and the background luminance levels at which dimming may be initiated and completed. These guidelines were developed from subjective assessments by traffic engineers.

To determine which intersection approaches should be dimmed, six characteristics of each intersection must be evaluated (Table 6), and a score is calculated by multiplying the applicable individual scores. Dimming is considered appropriate if the calculated score exceeds 0.03 and not appropriate if the calculated score is less than 0.01. If the score is between 0.01 and 0.03, the decision whether to dim is left to engineering judgment.

The sky luminance at which dimming may commence in urban and rural areas is presented in Table 7 for both proportional and stepped dimming controls.

Maximum intensities at night have not been investigated in any systematic, experimental manner. Analytic work by Jenkins appears to indicate that on a dark or poorly lit road (average pavement luminance of 0.1 cd/m^2), a maximum intensity of 250 cd is desirable, whereas on a well-lit road (average pavement luminance of 2 cd/m^2), a maximum intensity of 1,150 cd is desirable. This result would imply that on a well-lit road only the high intensity (12 in.) yellow signal needs to be dimmed, whereas on dark roads all high intensity and the yellow normal intensity signals should be dimmed (see Table 2). Jenkins pointed out that the intensity maximums apply to all colors of light (*18*).

Nighttime Distribution

Because no research on signal distribution has been performed at night, a separate recommendation is not possible (and definitely not desirable).

Phantom Limits

Cole, Clark, and Fisher have investigated the magnitude and sources of sun phantom both analytically and through physical measurements. However, only Fisher, in a controlled field experiment, has attempted to determine limits of phantom. A recommendation of 12:1 of red signal:yellow phantom is suggested by Fisher (*19–21*).

One problem related to phantom limits is that devices that control phantom (e.g., visors, louvers, etc.) also limit intensity. The only exception is the provision of increased beam intensity by use of a higher intensity source (*21*).

Driver Characteristics

Fisher and Fisher and Cole have suggested, based on considerable past research on elderly drivers, that an increase in

TABLE 6 SITE CHARACTERISTICS TO ASSESS DIMMING ADVISABILITY

FACTOR	LEVEL	SCORE
1. Signal Size	(a) 12 inch	.934
	(b) 8 inch	.466
2. Number of distracting background lights in 5-degree circle	(a) 0 - 1	.960
	(b) 2 - 5	.576
	(c) 6 or more	.114
3. Signal color	(a) yellow	.918
	(b) green	.618
	(c) red	.382
4. Approach speed	(a) 30 mph or less	.568
	(b) 31 - 45 mph	.412
	(c) 46 mph or more	.236
5. Rear-end/right-angle crash history	(a) 5 or fewer/year	.446
	(b) more than 5/year	.260
6. Number of signal faces	(a) 6 or more	.730
	(b) 5	.714
	(c) 4	.640
	(d) 3	.602
	(e) 2	.528

TABLE 7 LUMINANCE VALUES AT WHICH DIMMING MAY COMMENCE

LOCATION	PROPORTIONAL CONTROL Initiate	PROPORTIONAL CONTROL Complete	STEPPED CONTROL Initiate/Complete
URBAN	170	3	3
RURAL	340	3	3

NOTE: Values are in candelas per square meter.

intensity is necessary to ensure equal perception by the aged but that no increase in intensity will result in reactions identical to those of young drivers. The increase is probably between 1.5 and 3 times, depending on signal color and age (*7,8*).

Fisher and Cole have suggested, based on laboratory research by Cole and by Nathan, and analytic research by Clark, that protanopic drivers require four times more intensity than those with normal vision to ensure optimum responses, but that the intensities found optimum for drivers with normal vision will be adequate for those with color-defective vision (*5,8,22,23*). There is no data to relate driver characteristics to distribution requirements.

Freedman has quantified the effects of age and color vision deficiency on (minimum) nighttime intensities by means of laboratory, controlled field, and observational experiments, but no data exist to define nighttime maximums for elderly drivers (who are more sensitive to glare and could have lower maximums) or drivers with imperfect color vision (who might have higher maximums because of their reduced sensitivity to red) (*17*).

PRELIMINARY TRAFFIC SIGNAL STANDARD FOR ROUND SIGNALS

Table 8 presents a preliminary traffic signal standard for normal-speed roads (80 km/hr, distances of up to 100 m, and sky luminances of up to 10,000 cd/m²), and Table 9 presents a preliminary traffic signal standard for high-speed roads (100 km/hr, distances of up to 240 m, and sky luminances up to 10,000 cd/m²).

The recommendations in both tables are based on the scientific research described previously (except the item marked with an asterisk). For this item (luminance uniformity), there is no research to support a standard, so the corresponding values in tables 8 and 9 are taken directly from the present CIE standard (*15*). The color in all three tables is taken directly from the newest CIE color recommendations as illustrated in Table 1 (*15*).

The red intensity in Table 8 is the result of Cole's research on intensity and backplates (*5,12*), whereas the green and yellow intensities are based on the ratios derived by Fisher and Cole (*24*). The red intensity in Table 9 is the result of Hulsher's research on both intensity for high-speed roads and on use of backplates (*11*), whereas the green and yellow intensities are derived in the same manner as those in Table 8.

The distribution in Table 8 is derived from the research of Fisher (*13*), and the distribution in Table 9 is derived from the research of Hulsher (*14*). Both assume the use of a backplate.

Phantom limits are the result of Fisher's research (*21*), and dimming/night intensities are the result of the research by Freedman (*17*) and Jenkins (*18*). Tables 6 and 7 should be consulted to determine when to dim and at what background luminance levels dimming can begin.

TABLE 8 PRELIMINARY TRAFFIC SIGNAL STANDARD FOR NORMAL ROADS

SUBJECT		VALUE		COMMENT
COLOR		See Table 1		From Ref. 15
MAINTAINED DAYTIME PEAK INTENSITY (cd)		(1)		
RED		150		Assuming use of a backplate
GREEN		200		
YELLOW		450		
DISTRIBUTION (% of peak)	Horizontal	(degrees)	Vertical	
100	0 - 5		0 - 3	Assuming use of a backplate
50	5 - 10		3 - 5	
12.5	10 - 20		5 - 10	
7.5	20 - 30		10 - 20	
BACKPLATE				
SIZE		3 times signal diameter		
COLOR/REFLECTANCE		Mat black/reflectance < 0.16		
PHANTOM		12:1		Red signal: yellow phantom
UNIFORMITY OF LUMINANCE*		10:1		From CIE
DIMMING/NIGHT INTENSITY				
MINIMUM INTENSITY (cd)				
RED		50		May dim to these levels. See Tables 6 & 7
GREEN		95		
YELLOW		220		
MAXIMUM INTENSITIES (cd)				
DARK ROAD (0.1 cd/sq.m)		250		Should dim if intensities are above these levels
WELL LIT ROAD (2.0 cd/sq.m)		1150		

NOTE: Speed = 80 km/h, distance = 100 m, and sky luminance = 10,000 cd/m²

* From CIE Standard, Reference 15

(1) Including depreciation factor of 33%. If no depreciation factor is desired increase these values by 33%. (Equivalent to a new unit specification).

(2) Present ITE standards for 8 inch signals include red, green and yellow intensities > 157, 314 & 726 = cd respectively, all without backplates; signal distribution of 50% of peak at 11 degrees horizontal, 10 degrees vertical and 25% at 16 degrees horizontal, 13 degrees vertical and no discussion of depreciation, dimming, size or color of backplate, phantom level or uniformity level. ITE colors are similar to CIE and both standards can be met using the same equipment.

TABLE 9 PRELIMINARY TRAFFIC SIGNAL STANDARD FOR ROADS THAT CARRY HIGH-SPEED TRAFFIC

SUBJECT		VALUE		COMMENT
COLOR		See Table 1		From Ref. 15
MAINTAINED DAYTIME PEAK INTENSITY (cd)		(1)		
RED		600		Assuming use of a backplate
GREEN		800		
YELLOW		1800		
DISTRIBUTION (% of peak)	Horizontal	(degrees)	Vertical	
100	0 - 2.5		0 - 1.5	Assuming use of a backplate
67	2.5 - 4		1.5 - 2	
33	4 - 5		2 - 3	
25	5 - 7.5		3 - 4	
17	7.5 - 10		4 - 5	
8	10 - 20		5 - 10	
BACKPLATE		(see Table 8)		
PHANTOM		(see Table 8)		
UNIFORMITY OF LUMINANCE*		(see Table 8)		
DIMMING/NIGHT INTENSITY		(see Table 8)		

NOTE: Speed = 100 km/h, distance = 240 m, and sky luminance = 10,000 cd/m²

* From CIE Standard, Reference 15

(1) Including depreciation factor of 33%. If no depreciation factor is desired increase these values by 33%. (Equivalent to a new unit specification).

(2) Present ITE standards for 12 inch signals include red, green and yellow intensities > 399, 798 & 1848 cd respectively, all without backplates; signal distribution of 50% of peak at 11 degrees horizontal, 10 degrees vertical and 25% at 16 degrees horizontal, 13 degrees vertical and no discussion of depreciation, dimming, size or color of backplate, phantom level or uniformity level. ITE colors are similar to CIE and both standards can be met using the same equipment.

Depreciation factors of 33 percent are assumed [a loss of 25 percent, as noted in the CIE guide (*15*)]; hence, a specification (not a standard) could be prepared for new systems by increasing the intensities in tables 8 and 9 by 33 percent.

No effect of driver age or driver color vision deficiency has been included in the intensity requirements of tables 8 and 9 except for the night dimming values derived by Freedman. They are, however, included in the color standard.

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Research on the End of Life for Retroreflective Materials: A Progress Report

J. F. Paniati and R. N. Schwab

The status of the nationally coordinated program for retroreflectivity research is described. This program was developed under the guidance of the FHWA Office of Safety and Traffic Operations Research and Development. The goals of the program are to determine the end of life for retroreflective signs and markings and to develop the necessary measurement and management tools. Included are discussions of the human factors research to determine the end of life of retroreflective materials, an economic analysis of the impact of potential minimum requirements, mathematical modeling of the deterioration of sign materials, the development of computer software to manage sign inventories, and the design of new instruments to measure the retroreflectivity of signs and markings from a moving vehicle during daylight.

An examination of accident statistics confirms that driving at night is more dangerous than driving during the day. In 1987, about 23,000 fatalities, approximately 55 percent of all fatalities, occurred at night, although only 25 percent of travel occurred at night. This translates to a fatality rate (fatalities/vehicle miles traveled) that is more than three times higher at night than during the day.

It is known that a variety of factors contribute to this day/night disparity, including fatigue, intoxication, weather, and so on. However, drivers depend to a large extent on traffic control devices for warning, regulation, and guidance. As visibility conditions become poorer at night, this dependence increases. Many of the cues used by the driver for visual guidance in the day disappear at night. The addition of nighttime inclement weather and glare from opposing vehicles serve to compound the problem. The basic requirement for any traffic control device is that it must be visible and easily understood in time to permit the proper response by the driver. Because of gradual deterioration with age, many traffic control devices fail to meet this basic requirement at night.

This problem is compounded by the aging U.S. population. By 2030, the number of people older than 65 will more than double. Figure 1 shows the projected trend in the U.S. population to 2030. This population has grown up dependent on the motor vehicle and is expected to continue to use automobiles to meet daily mobility needs. Older drivers, as a group, exhibit a significant decrease in perceptual, cognitive, and psychomotor abilities, all of which are related to safe driving performance. Deteriorated signs cause partial difficulty for older drivers because of their decrease in perceptual ability.

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FHWA has recognized the need for traffic control signs and markings to be visible especially at night. Currently, the *Manual on Uniform Traffic Control Devices* (MUTCD) only requires that signs and pavement markings be retroreflectorized or illuminated. A comprehensive research program has been developed by the FHWA Office of Safety and Traffic Operations Research and Development to address the retroreflectivity issue. This research program is premised on motorists' need to detect and respond to traffic control devices in a safe and efficient manner.

The research studies in this program are categorized into several major topic areas (shown in Figure 2): minimum visibility requirements, implementation strategies, service life of signs, sign management system, traffic sign retroreflectometer, and pavement marking retroreflectometer. The program is being undertaken as a cooperative effort involving numerous funding sources, including FHWA research contracts, NCHRP efforts, Small Business Innovation Research (SBIR) funds, and Highway Planning and Research studies.

The research goal for this program is not just to obtain the information necessary to establish minimum retroreflectivity performance requirements, but to develop the tools (management programs and measurement devices) needed to implement them. The FHWA Office of Traffic Operations has provided technical guidance in the development of this program and will be responsible for directing implementation of the results. The status of the research is discussed next.

CURRENT RESEARCH

Minimum Visibility Requirements

In 1987, an FHWA contract study, Minimum Visibility Requirements for Traffic Control Devices, was initiated to determine (a) the minimum distances at which traffic control devices should be visible to the driver, and (b) the level of retroreflectivity that is necessary to satisfy these requirements.

This first step in this effort was to use the existing literature and the results from a controlled field experiment of driver maneuver times to model the driver demand. This demand is based on the distance required by the driver to detect the traffic control device, recognize the message, decide on the proper action, and complete the maneuver (if required). A computerized model of this process, the Minimum Required Visibility Distance (MRVD) Model, was developed. For a

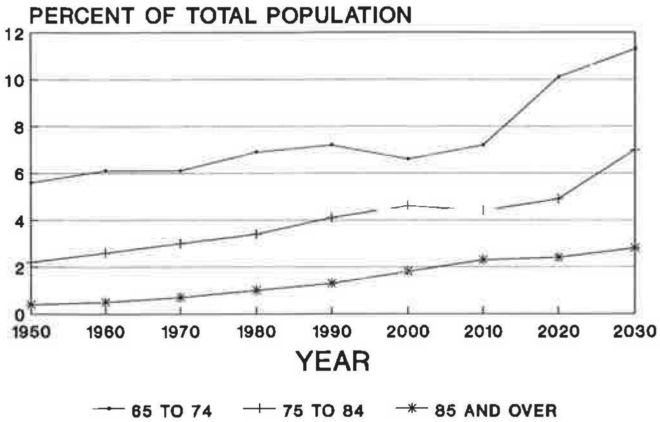

FIGURE 1 Number of elderly drivers as a percent of total population.

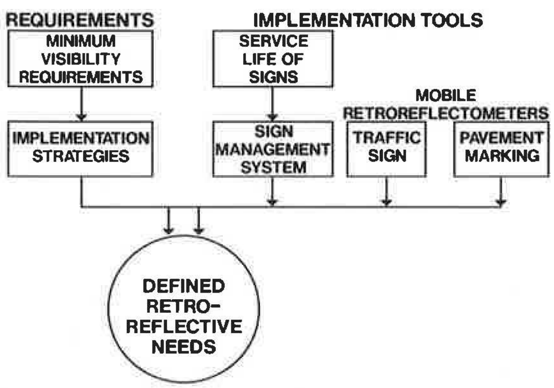

FIGURE 2 Organization of retroreflectivity program.

given traffic control device this model can be used to deter mine the minimum distance required by the driver to respond safely and efficiently.

The second part of the study was to determine the retroreflectivity level required to meet the driver demand. This is a complex process that involves many factors, including the vehicle headlight characteristics, the size and location of the sign, the roadway geometry, and the presence of glare from oncoming vehicles. A previously developed computer model (DETECT), which included these factors, was modified for use. The modified DETECT model was combined with the MRVD model to form a new model, Computer Analysis of the Retroreflectance of Traffic Signs (CARTS). With CARTS the user is able to determine the minimum luminance (and retroreflectivity) required for a specified sign.

To obtain the data necessary to calibrate and test this model, a series of laboratory and field studies were conducted. These studies established the relationship between the retroreflectivity level of a sign and its legibility and conspicuity distances. The final testing and calibration of CARTS has been completed, and the development of a retroreflectivity classification system is under way. It is anticipated that all MUTCD signs will be classified into approximately five categories. Each category will include minimum retroreflectivity values for each sheeting color. Factors considered in the classification will include sign placement, sign size, approach speed of traffic, and message complexity. The scheduled completion date for this project is April 1991.

Economic Assessment of Candidate Performance Requirements

Before the research results from the Minimum Visibility Requirements Study can be implemented, the potential national economic impact of candidate performance requirements must be assessed. The desire for increased driver safety must be balanced with the economic constraints of the highway agencies who must implement the requirements. A 1989 NCHRP research project, Implementation Strategies for Sign Retroreflectivity Standards, has been developed to provide this type of assessment.

As part of this study, retroreflectivity data from about 6,000 unwashed, in-service traffic signs were collected from September 1989 to April 1990. These signs were selected to be representative of various road types (Interstate, primary, urban, etc.) and jurisdictions (state, county, city) in the United States. These data were collected at 25 locations throughout the country.

In addition to obtaining retroreflectivity data, sign replacement cost and inventory practices data will be obtained. These data will be used to estimate the impact of establishing minimum retroreflectivity levels and develop economic-based priorities for sign maintenance budgets. The data collected will help determine how to maximize the benefit obtained from limited funding for sign maintenance. For example, should a highway agency spend its limited sign maintenance funds upgrading the most critical signs (e.g. stop, yield) on all roadways, or should it concentrate on upgrading all signs on heavily traveled roadways? Guidelines for staging the implementation of retroreflectivity requirements and an estimate of their effect on highway jurisdictions will be provided. This study was scheduled to be completed in the summer of 1991.

Service Life of Retroreflective Traffic Signs

One of the problems of managing retroreflectorized traffic signs is identification signs that need to be replaced because of loss of retroreflectivity. Sign replacement practices vary. Some agencies replace traffic signs on the basis of driver complaints, whereas others conduct subjective visual inspections at night. Still others arbitrarily replace signs every 5 to 7 years, which may result in removal of signs with several years of service life remaining or nonremoval of signs with insufficient retroreflectivity, which in turn results in a waste of money. If not replaced, deficient signs could lead to an accident for the motorist and a tort liability case for the highway agency. A study of tort liability cases in Pennsylvania found that signing deficiencies were cited as a primary factor in 20 percent of their tort actions, second only to pavement deficiencies. When only highway accidents in which a fatality or serious injury occurred are considered, signing deficiencies rank as the primary factor most often cited (41 percent).

A 1988 FHWA contract, Service Life of Retroreflective Traffic Signs, will model the deterioration of sign retroreflectivity. Retroreflectivity data for 6,000 signs with known dates of installation were collected at 20 sites in 8 geographic regions with varying climatic conditions. Predictive models will be developed for sign deterioration for various color and types of sheeting material. To date, it has been shown that sheeting age, solar radiation levels, and general area climate are the most important variables. The models show a large variation in their ability to predict in-service specific intensity of retroreflection (SIA). This is most likely because of the large initial variation in SIA values for new sheeting, dating errors in the sign inventories, and the limited number of sites surveyed.

The eight equations (four colors by two sheeting types) derived for predicting in-service SIA have R^2 values from 0.2 to 0.6. The goal of this effort was to develop predictive sign-life model(s) that could be incorporated into a sign management system (SMS), described next. Improvement in the predictive capabilities of the sign deterioration models described previously may require calibration with measurements from sample of in-service signs in the jurisdiction in question. This study was scheduled to be completed in March 1991.

Sign Management System

With 3.8 million miles of highways and the estimated 58 million signs used by highway agencies to assist drivers, the task to monitor the condition of signs is, to say the least, immense.

SMS is being developed to provide state and local highway agencies with a predictive tool for use in managing a sign inventory. This microcomputer-based system allows a sign inventory to be created and the age and condition of signs to be tracked. On completion of the study, it is envisioned that traffic engineers or those responsible for sign maintenance will be able to use SMS to determine which signs are likely to need replacement.

Field verification would also be used in making the final determination as to which signs need immediate replacement and which ones could be left in service. This procedure will assist highway agencies in locating deficient signs, using limited maintenance funds more efficiently, and projecting future budget needs.

The data base management portion of SMS has been developed. In its current form, this menu-driven, IBM-compatible system can be used to assemble and maintain a sign inventory. The final predictive software was expected to be operational in late 1991. A 1991 contract is planned to implement and evaluate the system in a small-to-medium sized community. A logic flow diagram of SMS is shown in Figure 3.

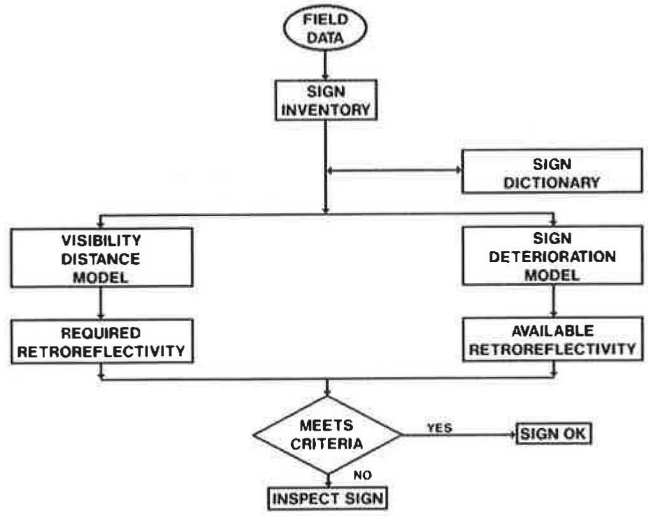

FIGURE 3 Logic flow of SMS.

Traffic Sign Retroreflectometer

Sign retroreflectivity can now be measured using a portable measuring device, but this device is not suitable for rapid measurement of numerous signs. The current instrument must be placed against the face of the sign to obtain a measurement. If the retroreflectivity of a large number of traffic signs must be measured in the field, then a new instrument is needed. A practical, safe, and cost-effective instrument for measuring sign retroreflectivity from a moving vehicle in daylight hours is currently being developed under an NCHRP research project, A Mobile System for Measuring Retroreflectance of Traffic Signs.

A laboratory, breadboard instrument has been developed. This device has been designed to operate during the daylight from a moving vehicle. It uses a CCD video camera to collect sign images, with an xenon, electronic flash source to provide a short burst of light sufficiently bright to overcome the daylight illumination. The video image is converted to a digital representation of the sign, analyzed with a microcomputer, and a histogram of the retroreflectivity distribution is output. By initially calibrating the instrument to a source with known retroreflectivity, the average legend and background retroreflectivity values can be obtained from the histogram. An example of a digitized image of a typical traffic sign and the corresponding histogram is shown in Figure 4.

In the first phase of the research, a laboratory prototype was developed and tested. During the second phase, the instrument was repackaged and installed in a van for field evaluation and assessment. The instrument and van, shown in Figure 5, were delivered to FHWA in December 1990. FHWA will work with state and local jurisdictions to evaluate the system and determine what modifications or enhancements are required.

Pavement Marking Retroreflectometer

The current state of the art for measuring the retroreflectivity of pavement markings is similar to the measuring of traffic sign retroreflectivity. Portable instrumentation is available for spot measurements, but the instrument must be placed directly on the marking. This does not allow for the rapid assessment of pavement marking retroreflectivity and can require extensive traffic control and driver delay. Through an SBIR study, Measuring Retroreflectivity of Pavement Markings, a laser-based technique for the measurement of pavement marking retroreflectivity from a moving vehicle has been developed.

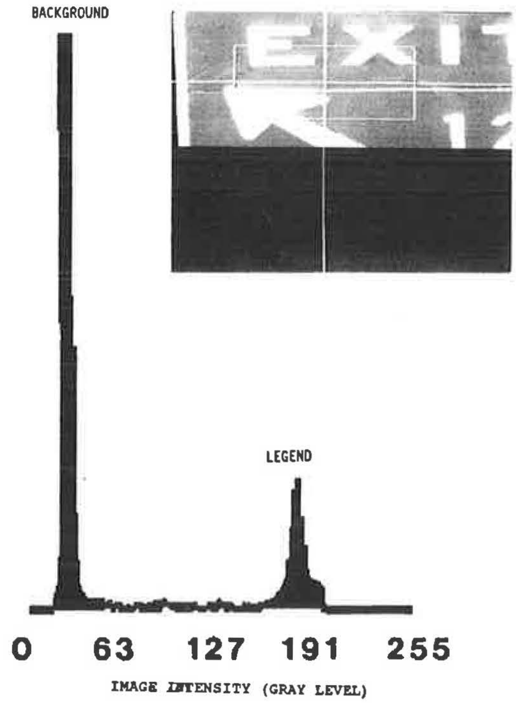

FIGURE 4 Example of sign retroreflectivity data plot.

FIGURE 5 Mobile sign retroreflectometer.

The prototype laser retroreflectometer, shown in Figure 6, is mounted on the side of a small truck with the bottom of the instrument 5 in. above the road surface.

The laser beam is projected off one surface of a rapidly spinning two-surfaced mirror to a point on the road approximately 30 ft in front of the instrument, making an angle with the road surface of 1°. The beam reflected from the road surface is redirected off the other surface of the rotating mirror to a photo detector. The beam scans each skip stripe approximately 3 times as the vehicle is driven down the highway at normal highway speeds, 20 to 55 mph. The geometry at which the pavement marking is viewed by the instrument is similar to what drivers view.

Work is currently under way to take the vast amount of data the system generates and reduces it to a data presentation format that will satisfy the needs of operating personnel. Statistical sampling procedures and plans for field testing the

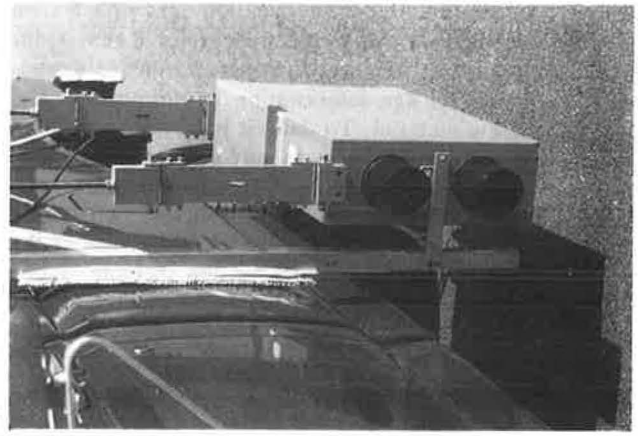

FIGURE 6 Laser pavement marking retroreflectometer.

equipment are being developed. It is expected that a commercial version of this instrument will be available next year.

A number of recent studies have indicated the point at which pavement markings are no longer adequate for driver guidance. For example, the results of NCHRP project 4-16 indicated that rating panels judged the pavement markings to be inadequate for a 45-mph road when their retroreflectometer reading dropped below 100 mcd/m^2/lux. What is now required is the agreement by professionals working in the field on what is a practical retroreflectivity level at which lines should be refurbished. This level must allow adequate time for scheduling the remarking to ensure that the line will not reach the level determined to be unsatisfactory for visual guidance before the next inspection and marking period.

DEMONSTRATION ACTIVITIES

Subsequent to the completion of the above described research, extensive demonstration and implementation activities will be undertaken. The emphasis will be on sign inspection and maintenance training courses and the demonstration of the instrumentation and management and inventory tools that have been developed. Two activities have been completed to date.

Workshops

Two 2½-day regional workshops on field inspection and rehabilitation of traffic control devices were held. At these workshops the progress and current status of research and development efforts to determine performance requirements for in-service retroreflective traffic control devices were reviewed and discussed. Other areas discussed include material selection, improved inventory techniques, field assessment techniques, current state programs, and techniques for refurbishing signs.

Retroreflectivity Manual

A manual has been developed to provide highway personnel with a better understanding of many traffic sign problems.

The manual covers principles of retroreflection; selection of proper material type; specifications and testing procedures; fabrication methods, installation, handling, and stockpiling techniques; alternative inspection methods; and sign inventory, maintenance, and replacement guidelines.

This manual, *Retroreflectivity of Roadway Signs for Adequate Visibility: A Guide,* FHWA Report FHWA-DF-88-001, was developed for use on Federal Highway Projects, but it may also be used by state and local highway personnel responsible for traffic signs.

Ongoing Activities

Two additional implementation activities are under way. A handbook is being developed to describe and explain innovative materials, equipment, and procedures used by various public agencies in fabricating, installing, and maintaining signs. This handbook will be a helpful reference tool for other jurisdictions to become aware of new techniques that could save time or money in producing and maintaining signs.

The second activity is a revision and updating of the *Roadway Delineation Practices Handbook,* first published by FHWA in 1981. This new edition will incorporate much of the new information on durable materials obtained under NCHRP project 4-16, Service Life and Cost of Pavement Marking Materials. It will also greatly expand the discussion on field evaluation techniques and determining the service life of pavement markings.

CONCLUSION

This research was undertaken to learn more about the problems found in night driving and the problems associated with reflectorized traffic control devices. The human factor needs and requirements for safe nighttime driving were reviewed and evaluated. The program is being used to address the technical aspects of the problem and the financial and managerial problems that would occur if in-service minimum retroreflectivity performance levels were to be adopted. FHWA will work with other organizations interested in this problem, for example, Institute of Transportation Engineers, NCHRP, National Committee on Uniform Traffic Control Devices, AASHTO, and others, to ensure that the results of this program are implemented reasonably and prudently, so that nighttime highway safety can be improved.

Retroreflectivity Requirements for Pavement Markings

JOHNNY R. GRAHAM AND L. ELLIS KING

Subjective evaluations by 59 observers and quantitative measurements of in-place roadway markings were made in order to determine minimum field luminance and retroreflectivity levels for pavement markings. A minimum luminance value was also determined for the same observers through subjective evaluations and quantitative measurements under controlled and repeatable laboratory conditions. For the field test, more than 90 percent of the subjects rated a marking retroreflectance of 93 mcd/m^2/lx as adequate or more than adequate for night conditions. More than 98 percent of the subjects rated all locations having a marking luminance of 3.84 cd/m^2 or greater as adequate or more than adequate, corresponding to a measured retroreflectivity of 94 mcd/m^2/lx. For the laboratory study, more than 90 percent of the subjects rated the simulated markings with a luminance of 0.38 cd/m^2 as adequate or more than adequate. Subjects used in this research represented a relatively young population, and the study was conducted under ideal field conditions. It is likely that an older driver, operating in a real-world driving situation, would require a retroreflectivity value higher than 93 mcd/m^2/lx.

The nighttime accident rate is more than three times the daytime rate when computed on a mileage basis. Factors contributing to this statistic may include use of alcohol or other drugs and driver fatigue. However, the information required by drivers is visual in nature, and the poor visual conditions at night may be considered a major contributing factor. The driver depends on roadway markings for much of the information required for guidance during nighttime driving.

Little work has been reported in the literature concerning the relationship between retroreflectivity and driver perception of roadway marking adequacy (*1–5*). There is no widely accepted minimum adequate retroreflectivity value in the United States.

In this research, subjective evaluations by 59 observers and quantitative measurements of in-place roadway markings were made in order to determine minimum field luminance and retroreflectivity levels for pavement markings. A minimum luminance value was also determined for the same 59 observers through subjective evaluations and quantitative measurements under controlled and repeatable laboratory conditions, and an equation was developed to express the relationship between the field and laboratory luminance subjective evaluations.

FIELD INVESTIGATION

The field experiment provided objective measurements of the retroreflectivity and luminance of existing roadway markings and subjective evaluations of the adequacy of the markings. The initial step in the field investigation was to establish an observation course, with a broad range of marking retroreflectivity values, that could be traversed in approximately 40 min at a safe and comfortable night speed. Each marking on the observation course met the following criteria:

1. Each marking location was on a straight section of roadway on a uniform grade.
2. The minimum length of each marking location was 200 ft.
3. There was no supplemental lighting near the location.

A number of suitable locations were chosen, and retroreflectivity readings were made at 15-ft intervals on each with a Mirolux 12 Retroreflectometer. Average retroreflectivity readings for the locations were used to determine the final observation route, which included 20 observation locations spaced over a distance of approximately 20 mi.

Retroreflectivity measurements were easily made with a Mirolux 12 Retroreflectometer during daylight hours. Luminance measurements were made at night using a Gamma Scientific Telephotometer Model 2000 mounted at eye level between the driver and passenger positions in the front seat of a 1980, 4-door, Plymouth Volare. Luminance measurements could not be made from a moving vehicle, and traffic prevented stopping on the roadway for the necessary amount of time required to make a stationary measurement. For safety reasons the vehicle was parked on the roadway shoulder while measurements were recorded at viewing distances of 50, 75, and 100 ft. Of the 20 marking locations on the observation route, 11 were considered to have suitable shoulder conditions for safe parking and for obtaining luminance measurements. A study was conducted in a dark parking lot to relate the measurement made from an actual driving position to the measurements made from the roadway shoulder.

Subjective evaluations of each location on the test route were made at night. Paid observers were secured through posted and verbal advertisements, and the only criterion was that each observer have a valid driver's license. A total of 59 observers, 43 male and 16 female, ranging in age from 19 to 47 with an average age of 24.5 years, were included in the study. Eight of the observers took part in a pilot study.

The observers met at a designated location at an assigned time in groups of three. Each observer was given a set of written instructions, a statement of informed consent, and a clipboard with a recording form. A pencil and a penlight were attached to the clipboard by strings. The observers were given tape-recorded instructions in addition to the written version in order to ensure consistency and understanding. The in-

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structions gave the purpose of a roadway marking, a description of observation locations, and an explanation of the method of recording responses. A selected evaluation response of (a) less than adequate, (b) adequate, or (c) more than adequate was based on the results of a pilot study for eight observers. Observers were informed that they should remain silent during the testing, wear glasses or contact lenses if they normally did so to drive, and record their evaluations promptly. It was emphasized that there were no right or wrong answers, only the observer's personal opinion. At the end of the instruction period each observer was asked if he or she had procedural questions, which were answered, but no questions pertaining to the adequacy of roadway markings were allowed. The observers were instructed in how to fill out the observation recording forms and how to use the penlight, which was used to enable observers to see to record information at night. The bulb was covered with red translucent plastic to minimize any effect on the observer's night vision.

The same driver was used for all observers, and vehicle speed was a safe, comfortable speed for roadway conditions as determined by the driver and within posted speed limits. No attempt was made to drive at a constant speed because the observer route was on public roadways and other traffic was present. Opposing traffic was infrequent and random and no vehicles were closely followed. Low-beam headlights were used at all times. The beginning of each observation location was announced approximately 300 ft in advance. An observation trip typically lasted 35 to 40 min, and all trips were made on clear, cold, dry nights.

After being instructed, the observers were seated in the front right, rear left, and rear right passenger seats of the test vehicle. This seating arrangement had proved satisfactory during the pilot study. Observers were initially shown one of the reflective markings used to mark the beginning of observation locations in order to acquaint them with what they would be looking for on the observation course. The test vehicle was stopped approximately 100 ft short of the example reflective marking, and the observers were informed that this was representative of what they would see to indicate the beginning and ending of each observation location. Observers were also informed of the distance to the example marking to better familiarize them with the length of an observation location and the distance from the location at which advance notice would be given on the course. The driver then proceeded while the observers evaluated each location by circling on the recording form the proper category best describing their perception of marking adequacy.

LABORATORY INVESTIGATION

The laboratory experiment was designed to evaluate simulated roadway markings of varied luminance. A dark tunnel, 16-ft long by 4-ft wide by 8½-ft high, was constructed of heavy black cloth and hung from the ceiling in a large laboratory room. Inside the tunnel at one end was a 3-ft by 6-ft platform 2-ft 6-in. above the floor, which supported a simulated roadway surface on which strips of roadway marking tape could be placed.

At the opposite end of the tunnel was an observation booth constructed of plywood and heavy black cloth. The booth had a 2-in. high by 4-in. wide closable viewing window through which the simulated roadway surface and markings could be observed. The observation booth was approximately 6-ft long by 4-ft wide by 8½ ft high with a table below the observation window. An adjustable height chair was provided for the observer in order to adjust the eye height of all individuals to the same level. The geometry of the tunnel was designed to simulate a roadway edge line marking as viewed by a driver from a distance of 50 to 75 ft.

In order to vary the luminance of the markings, a lighting system was mounted on the outside vertical plywood surface of the observation booth inside the dark tunnel. A shielded reflector-floodlight was mounted on each side and below the observation window. The intensity of the light output of the reflector-flood lamps was controlled by means of a precision rheostat and monitored by a digital multimeter. Because the reflective properties of each roadway marking were constant, a change in incident light intensity resulted in a proportional change in the luminance of the marking.

Test markings, 6-ft long by 1-in. wide, were cut from 3M Company's Stamark 5730 White and 5731 Yellow roadway marking tape. Background colors were gray and black to simulate portland cement concrete and asphalt concrete roadway surfaces.

Because the relationship between an observer's perception of roadway marking adequacy in the laboratory and in the field was unknown, the range of laboratory luminances was from one that was barely visible to the human eye, 0.01 cd/m^2 to an obviously high luminance, 3.00 cd/m^2. The lower luminance value was based on several individuals' judgment of the level at which they could barely see the markings, while the upper luminance value was the maximum that could be produced by the lighting system in the tunnel.

The luminance values for the simulated markings were measured using the Gamma Scientific telephotometer in the observer booth. The optical head was directed through the window toward the marking, the same orientation as the observer's eye during an observation. Luminance values were measured at three locations along the simulated roadway marking and averaged. Once the luminance values at the limiting conditions were fixed, a number of luminance conditions within the range were selected and both the luminance and voltage producing the condition were recorded so that each value could be reproduced later.

Subjective evaluations of marking adequacy for varying luminance conditions were made under controlled laboratory conditions for each of the 59 observers who participated in the field study. Nine of the observers took part in a pilot study. The observers were given written instructions similar to those used in the field study. Tape-recorded instructions, which were identical to the written instructions, were also played for each observer. The instructions gave the purpose of a roadway marking, a description of the testing procedure, and the method of recording an evaluation of (a) less than adequate, (b) adequate, or (c) more than adequate for each marking. Observers were informed that they would have 5 sec during which time the window of the observation booth would be open to make an observation and then approximately 20 sec to record their evaluation during which the window would be closed. They were given a clipboard with a recording form and provided a pencil and penlight. The observers were instructed to promptly record their evaluation after each observation. Observers were permitted to ask procedural questions but none pertaining to the adequacy of roadway markings. After being instructed, the observer was seated on the adjustable height chair in the observer booth, and his or her eye level was adjusted to the predetermined elevation. The curtain door of the booth was closed, and laboratory lights were turned off. After completion of 20 observations, the laboratory lights were turned on, the evaluation recording form was collected, and the observer was paid for his or her services.

RESULTS

Figure 1 shows the percentage of observers rating each field location as adequate or more than adequate. The x-axis is nonlinear, and the values shown are the average retroreflectance values for each of the 20 individual locations. This histogram shows a well-defined break-point, with all locations having retroreflectance values greater than 93 mcd/m²/lx being rated as adequate or more than adequate by more than 90 percent of the observers. Location 12, with a retroreflectance value of 137 mcd/m²/lx, was rated as adequate or more than adequate by all observers, as were all locations with values of 180 or greater.

Figure 2 is a graphic portrayal in which average retroreflectivity versus average subjective rating has been plotted for each field location. These ratings were produced by assigning numerical values of 1, 2, and 3 to the subjective ratings of less than adequate, adequate, or more than adequate, respectively, and then using the numerical values to calculate an average value for each of the 20 field locations. Regression analysis on the data gives the following logarithmic equation:

$$Y = 0.641 \ln(X) - 1.018 \quad (1)$$

where X is the retroreflectance (mcd/m²/lx) and Y is the average subjective rating. The resultant curve has a coefficient of determination of 0.89 and a standard error of estimate of 0.19. The lack of fit in the critical region of 100 mcd/m²/lx is readily apparent. When Equation 1 is used to calculate the

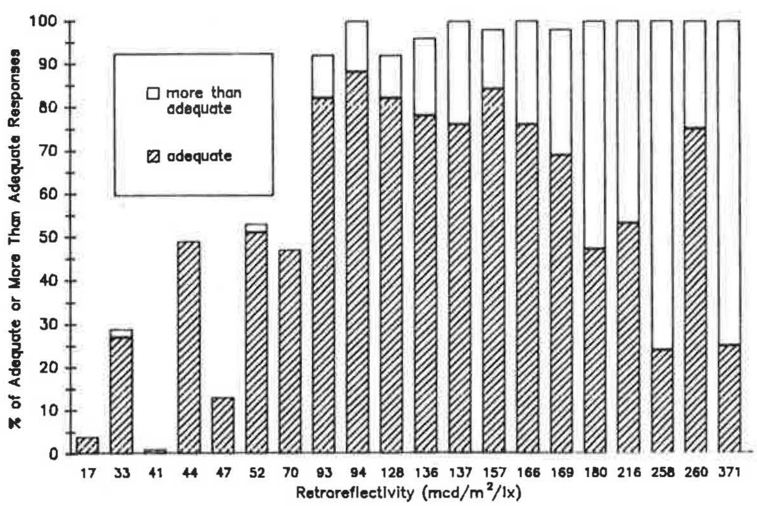

FIGURE 1 Field study retroreflectivity subjective evaluation.

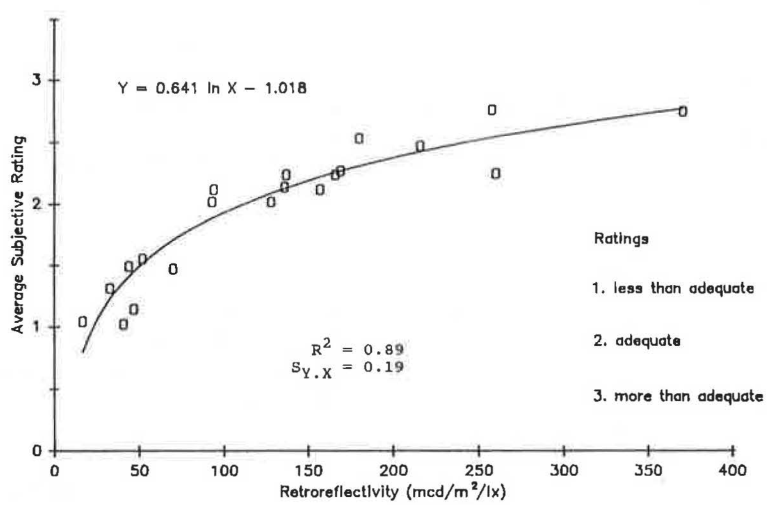

FIGURE 2 Average subjective rating of field retroreflectivity.

retroreflectance corresponding to an average subjective rating of 2, the result is 111 mcd/m²/lx.

Figure 3 shows the percentage of observers rating each field location as adequate or more than adequate. The x-axis is nonlinear, and the values shown are the average luminance values for each location. This histogram shows a definite break-point, with all locations having luminance values greater than 3.84 cd/m² being rated as adequate or more than adequate by 98 percent or more of the observers.

Figure 4 is a graphic portrayal in which average luminance versus average subjective rating has been plotted. Again, these ratings were produced by assigning the numerical values of 1, 2, and 3 to the subjective ratings of less than adequate, adequate, or more than adequate, respectively, and using the numerical values to calculate an average value for each of the 11 field locations for which luminance was measured. Regression analysis on the data gives the following logarithmic equation:

$$Y = 0.50 \ln(X) + 1.22 \quad (2)$$

where X is the luminance (cd/m²). The resultant curve has a coefficient of determination of 0.92 and a standard error of estimate of 0.14. When Equation 2 is used to calculate the luminance corresponding to an average subjective rating of 2, the result is 4.7 cd/m².

Figure 5 shows the percentage of observers who rated each laboratory simulation as adequate or more than adequate. Again, the x-axis is nonlinear, and the values shown are the average luminance values for each simulation. This histogram shows break-points at luminances of 0.11 and 0.38 cd/m². Starting at the 0.11 cd/m² luminance value, all values were rated adequate or more than adequate by more than 75 percent of the observers. Beginning with the 0.38 cd/m² value, more than 90 percent of the observers rated the simulations adequate or more than adequate. From a luminance value of 0.45 cd/m² onward all observers rated simulations as adequate or more than adequate except for the 0.75 cd/m² simulation, which was rated as adequate or more than adequate by 98 percent of the observers. From 1.52 cd/m² onward most observers rated markings as more than adequate.

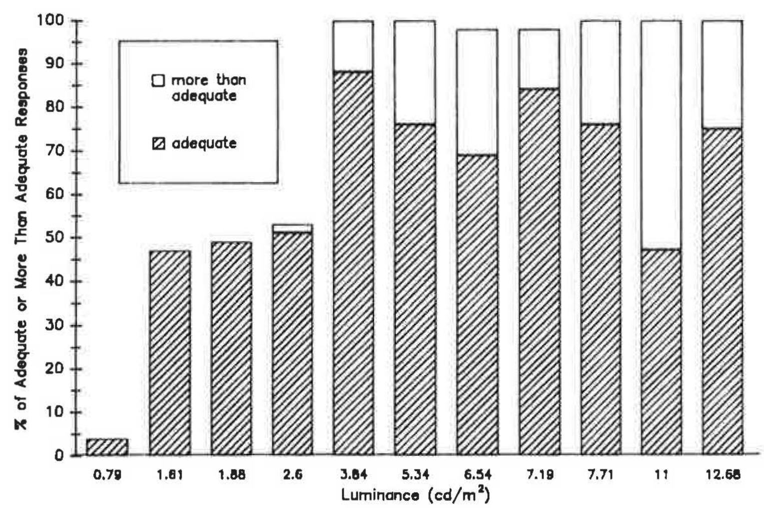

FIGURE 3 Field study luminance subjective evaluation.

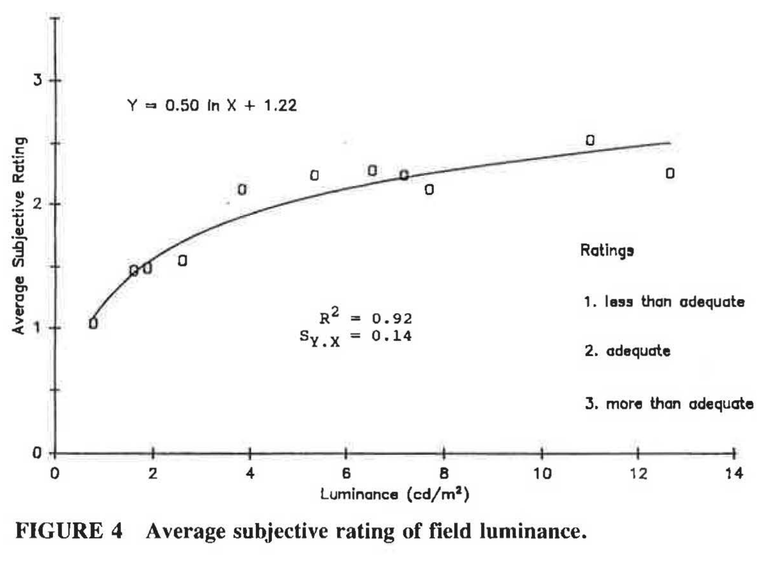

FIGURE 4 Average subjective rating of field luminance.

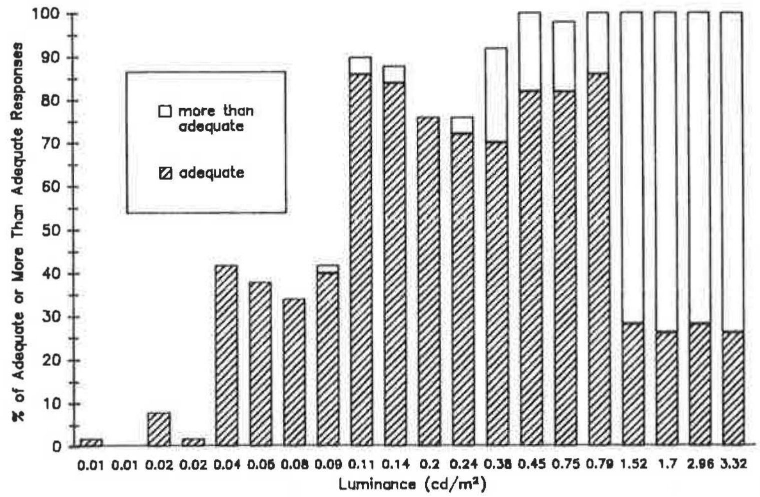

FIGURE 5 Laboratory luminance study subjective evaluation.

Figure 6 is a graphic portrayal in which laboratory luminance versus average subjective rating has been plotted. Regression analysis on the data gives the following logarithmic equation:

$$Y = 0.323 \ln(X) + 2.39 \quad (3)$$

The resultant curve has a coefficient of determination of 0.95 and a standard error estimate of 0.14. When Equation 3 is used to calculate the luminance corresponding to an average subjective rating of 2 in the laboratory setting, the result is 0.30 cd/m^2.

LABORATORY LUMINANCE VERSUS FIELD LUMINANCE

The relationships previously expressed in equations 2 and 3 were determined from 20 observations by each of 50 observers in the laboratory experiment and 11 observations by each of 51 observers in the field experiment. Letting X_1 represent field luminance and X_2 represent lab luminance the equations can be written as follows:

$$Y = 0.500 \ln(X_1) + 1.22 \quad (4)$$

$$Y_2 = 0.323 \ln(X_2) + 2.39 \quad (5)$$

Setting the average observer ratings Y_1 and Y_2 equal to each other and solving for X_1 results in Equation 6, which gives the relationship between the laboratory and field observations.

$$X_1 = 10.4\, X_2^{0.65} \quad (6)$$

Thus, the relationship between subjective rating of the adequacy of roadway markings based on luminance in the field and luminance in the laboratory is the power curve expressed as Equation 6 and shown in Figure 7.

If Equation 6 is used to convert the laboratory luminance value of 0.30 cd/m^2, the value corresponding to a subjective rating of 2, to a field luminance value, results in a field lu-

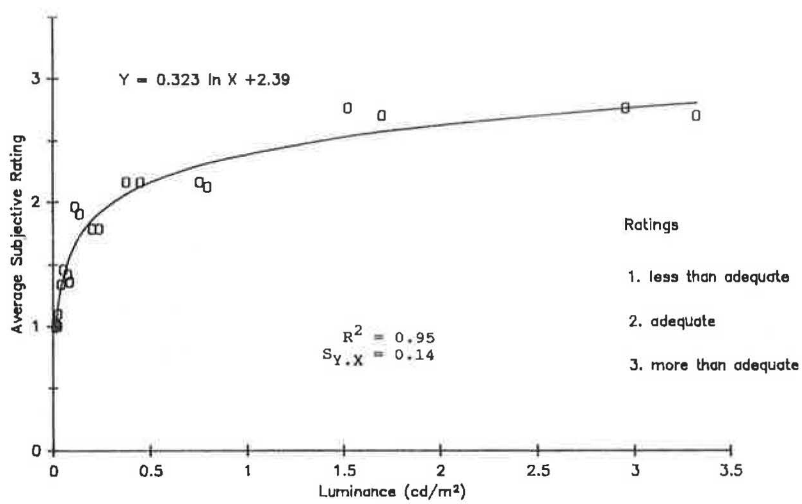

FIGURE 6 Average subjective rating of laboratory luminance.

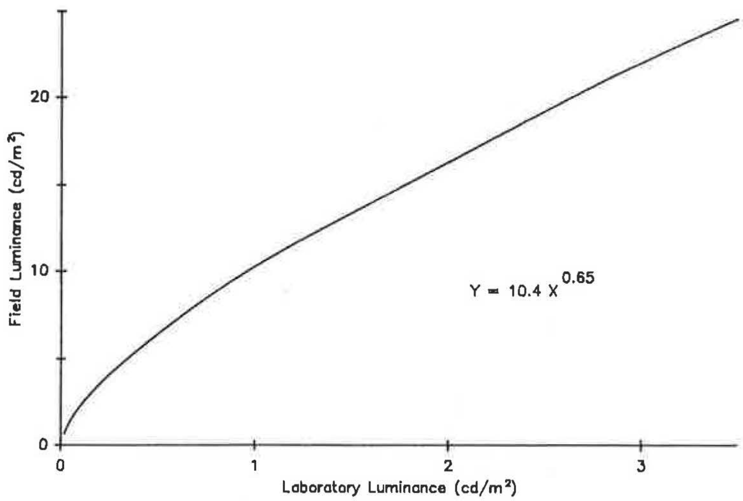

FIGURE 7 Field versus laboratory subjective rating.

minance of 4.76 cd/m². This relationship can also be observed in Figure 7 when for a subjective rating of 2 the value of laboratory luminance is approximately 0.3 cd/m² and that for the field luminance is approximately 4.7 cd/m². For this average subjective rating of 2.0 the field luminance to laboratory luminance ratio is 15.9. Equation 6 may be used to calculate additional "field factors" ranging from 13.2 at a laboratory luminance level of 0.5 cd/m² to 5.92 at a level of 5 cd/m².

SUMMARY

For the field test, more than 98 percent of the subjects rated all locations having a marking retroreflectivity of 93 mcd/m²/lx or greater as adequate or more than adequate. This retroreflectivity corresponds to an average luminance of 3.84 cd/m².

For the laboratory study, more than 90 percent of the subjects rated the simulated markings with a luminance of 0.38 cd/m² as adequate or more than adequate. The lowest luminance value to be rated as adequate or more than adequate by all observers was 0.45 cd/m². All values greater than 1.52 cd/m² were rated as more than adequate.

The relationship between the subjective evaluation of field luminance and the subjective evaluation of laboratory luminance can be expressed mathematically. The equation may be used to relate controlled laboratory study results to expected field results.

CONCLUSIONS

A roadway marking retroreflectivity value of 93 mcd/m²/lx may be considered as a minimum level for nighttime conditions on the basis of the field and laboratory evaluations and measurements reported in this study. However, it should not be considered as a recommended minimum value because the subjects used in this research represent a relatively young population and were aware that they were participating in a research study that was being carried out under "ideal" conditions in the field. It is likely that older drivers, operating in real-world situations, would require a higher value.

ACKNOWLEDGMENTS

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Evaluation of Reflective Sheetings

ASHWANI K. SHARMA

In 1976 a photometric evaluation of reflective sheetings was begun. Included in the study were 9 white and 10 yellow reflective sheetings. For each color, five 15-in. square aluminum-backed panels were prepared and placed on vertical racks on the sign shop roof in Wisconsin Rapids, Wisconsin. The panels were first put in place near the end of January 1977. From 1977 to 1982, semiannual photometric evaluations of the sheetings were performed with a photometer. From 1983 to 1987, annual reflectivity measurements were obtained with a retroreflectometer. The amount of cold cracking also was measured. All photometer and retroreflectometer tests were taken at a divergence angle of 0.2 degree and at incidence angles of −4 and +30 degrees. In addition to the five panels for each color sheeting, each white sheeting had five panels prepared for the purpose of studying the effect of stone bruising on cold cracking. Artificial stone bruises were made on each of these panels (four bruises per panel, one bruise per quadrant) by means of a dull center punch. (The artificial bruise damaged the sheeting but not the aluminum.)

During the early 1970s, the introduction of various sign sheeting brands, including various grades within each brand, created for the then Wisconsin Department of Highways (DOH) the need of an evaluation procedure for reflective sheeting. Wisconsin Department of Transportation (DOT) experience, plus that of other states, indicates that any evaluation procedure for reflective sheeting must incorporate more than just an initial determination of sheeting qualities, such as reflective intensity. Initial determinations of sheeting qualities cannot help predict the long-term impact of the environment on the behavior and effective service life. Some states have tried to speed up the effects of time and weather by testing the reflective materials in weatherometers. Unfortunately, in 1976 no consistent or reliable correlation existed between weatherometer results and actual performance.

Since the initiation of this study DOT did purchase a photometer, making it possible to quantitatively measure the reflective intensity of sign sheetings. Reflectivity measurements from 1977 to 1982 on signs were made semiannually by using a photometer. Reflectivity measurements from 1983 to 1987 were made annually by using a Gamma Scientific retroreflectometer (model 910). Reflectivity readings from 1977 to 1982 were made compatible with retroreflectometer readings by applying appropriate correction factors.

OBJECTIVES

The objectives of this study were to (a) determine the initial reflective intensities of various brands of reflective sheetings (and for various grades and colors within certain brands), (b) determine the time-loss of reflective intensity of various sheetings exposed to the environment, and (c) determine the cold-cracking propensities of the sheetings.

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SCOPE

The basic plan for this study was to place a number of signs with various reflective sheetings in the field and test them semiannually or annually for reflective intensity. The signs did not contain any messages because they interfere with photometer readings. Because the signs were blank and could not be used for actual highway signing, they were placed in a nontrafficked outdoor exposure site—the roof of the District Sign Shop in Wisconsin Rapids. The signs were placed in racks (15 to 20 signs per rack), which were standing vertically and facing south. The racks were constructed so that the signs could easily be removed for evaluation.

This study was conducted for 10 years to adequately document the loss of reflectivity with time, especially to the point at which the signs were no longer considered adequate for actual signing.

The combination of brands, grades, and colors of sheeting that were tested is presented in Table 1. Five signs of each sheeting type were tested for reflective intensity. In addition to reflectivity tests on the various sheeting types, five white samples from each brand (engineer grade for those brands had multiple grades) of sheeting were selected for stone-bruising and cold-cracking studies.

Thus, the total number of signs used in the test was 125. The test signs were aluminum backed and 15 in. square. The size of the sign was determined by the area actually tested (a 10.5-in. circle) with the photometer and retroreflectometer. All photometer and retroreflectometer tests were taken at a divergence angle of 0.2 degree and at incidence angles of −4 degrees and +30 degrees.

STANDARD SPECIFICATIONS

The DOT 1975 Standard Specifications Section 637.2.2.1, Standard Reflective Sheeting, states that sign face materials shall comply with Federal Specification L-S-300A. A newer federal specification, L-S-300B, may be referred to by the state in future supplemental specifications. Because the state specifies compliance with the federal specification, it is desirable to develop a test program complying as closely as possible with L-S-300B (to ensure measurements with an accuracy and precision as high as possible with the state's photometer).

TABLE 1 COMBINATION OF BRANDS, GRADES, AND COLORS OF SHEETING TESTED

Sheeting Type	Sheeting Code	Brand Name	Grade	Color	Sign Numbers	Stone Bruised Sign Numbers
1	A	Adcolite	Engineer	White	1-5	91-95
2			Engineer	Yellow	46-50	---
3	X	Fasign	Engineer	White	6-10	96-100
4			Engineer	Yellow	51-55	---
5	O	Fasign	Construction	White	11-15	
6			Construction	Yellow	56-60	
7	K	Maclite	--	White	16-20	101-105
8			--	Yellow	61-65	
9	J	Scotchlite	Type "H"	White	21-25	
10			Type "H"	Yellow	66-70	
11	F	Scotchlite	Engineer	White	26-30	106-110
12			Engineer	Yellow	71-75	
13	D	Scotchlite	Level "B"	White	31-35	
14			Level "B"	Yellow	76-80	
15	Y	Seibulite	---	White	36-40	111-115
16			---	Yellow	81-85	
17	T	Toshiba	Engineer	Yellow	86-90	
18	W	Kewalite	Engineer	White	126-130	121-125
19		Kewalite	Engineer	Yellow	131-135	

PROCEDURES

Because reflective sheeting does not have a uniform reflective intensity from batch to batch, roll to roll, or even within the same roll, it was important and special efforts were made to fabricate the test signs from broad samples of sheeting. Thus, the sheeting for duplicate signs (signs of the same sheeting type) was taken from various transverse and longitudinal positions in the same roll and from different rolls and batches. Shortly after sign fabrication and before field placement the signs were tested with the photometer to establish the initial reflective intensity. On completion of the initial testing the signs were placed in their respective positions in the racks (placed vertically and facing south). The signs remained in the racks for 6 months. They were then washed with water and a sponge. After washing, the signs were taken from the racks, placed in their respective slots in the carrying case and taken to the Research Section in Madison. After testing, the signs were returned to the racks. The same procedure was used in subsequent testing. Great care was exercised in the handling of the signs to ensure that they were not damaged.

Signs set apart for stone-bruising studies were bruised artificially with a spring-loaded center punch to simulate actual stone bruising. The point of the punch was ground to a blunt surface so that it bruised the sheeting but did not dent the aluminum. The artificial stone bruising was done after fabrication of the signs and before testing for initial reflective intensity. (The same testing procedure was followed for these signs as was followed for the nonbruised signs). Each sign made specifically for stone bruising received four artificial bruises. The number of linear inches of cold cracking was documented annually for both the stone bruised and the regular signs.

DISCUSSION OF RESULTS

The focus of this report is on findings, not the causes giving rise to those findings. The average reflective intensity values are presented in Table 2 and are in units of candlepower per foot – candle per square foot ($cp/ft - cd/ft^2$). The cold cracking values are presented in Table 3 and are in units of linear inches per square foot. Discussions of reflectivity and cold cracking for each sheeting type follow.

Adcolite Engineer Grade (White)

Adcolite white sheeting proved to be durable, but the reflectivity was not as high as some of the other sheetings in the test. When reflectivity was measured with an incidence angle of −4 degrees, it had a high value of $104.4R$ (R = retroreflectivity = $cp/ft - cd/ft^2$) and a low value of $73.6R$, which was above the state's specification (compliance with Federal Specifications L-S-300A) for new sheeting. When reflectivity

TABLE 2 REFLECTIVITY DATA

		Incidence Angle					
		−4 Degrees			+30 Degrees		
Brand	Grade	White	White Stone Bruised	Yellow	White	White Stone Bruised	Yellow
March 1, 1977 Test							
Adcolite	Engineer	92.9	95.3	53.8	35.6	36.5	29.2
Fasign	Engineer	110.7	113.6	61.3	65.3	66.9	32.0
Fasign	Construction	110.8	[a]	62.5	69.5	[a]	32.4
Kewalite	Engineer	[a]	[a]	[a]	[a]	[a]	[a]
Maclite	Engineer	128.6	127.1	85.1	76.8	84.4	76.4
Scotchlite	Engineer	102.0	101.1	74.6	53.8	55.0	35.0
Scotchlite	Level B	66.6	[a]	72.1	40.5	[a]	28.4
Scotchlite	Type H	301.6	[a]	208.5	213.6	[a]	180.3
Seibulite	Engineer	114.4	116.9	85.1	66.4	66.5	53.6
Toshiba	Engineer	[a]	[a]	62.7	[a]	[a]	47.0
April 20, 1983 Test							
Adcolite	Engineer	85.5	93.2	61.1	27.5	29.2	31.1
Fasign	Engineer	55.2	51.1	21.9	29.0	29.0	11.7
Fasign	Construction	69.4	[a]	25.4	39.3	[a]	12.8
Kewalite	Engineer	124.5	124.4	111.2	65.2	65.2	55.4
Maclite	Engineer	[b]	[b]	4.5	[b]	[b]	4.1
Scotchlite	Engineer	102.0	102.3	79.8	55.4	56.7	34.0
Scotchlite	Level B	49.9	[a]	81.3	32.9	[a]	33.3
Scotchlite	Type H	275.9	[a]	218.5	183.3	[a]	179.2
Seibulite	Engineer	78.1	73.6	87.1	59.5	56.1	60.4
Toshiba	Engineer	[a]	[a]	105.1	[a]	[a]	62.6
March 18, 1987 Test							
Adcolite	Engineer	73.6	81.6	51.6	23.1	23.8	26.6
Fasign	Engineer	[b]	[b]	[b]	[b]	[b]	[b]
Fasign	Construction	[b]	[a]	[b]	[b]	[a]	[b]
Kewalite	Engineer	23.6	32.9	22.4	12.1	15.6	13.3
Maclite	Engineer	[b]	[b]	[b]	[b]	[b]	[b]
Scotchlite	Engineer	90.2	87.2	65.9	48.9	50.3	32.1
Scotchlite	Level B	36.0	[a]	63.1	28.3	[a]	31.1
Scotchlite	Type H	243.9	[a]	165.2	139.9	[a]	149.1
Seibulite	Engineer	43.6	40.2	84.4	43.4	39.6	55.9
Toshiba	Engineer	[a]	[a]	[b]	[a]	[a]	[b]

NOTE: Values are in units of candlepower per foot-candle per square foot.
[a]Not tested.
[b]Retired because of poor results.

was measured at an incidence angle of +30 degrees, the high value was 36.5*R* and the low value was 23.1*R*. The low value is below the specifications for new sheetings, but is still above the usable specifications. Stone bruising had little effect on the reflectivity. Adcolite was one of the first sheetings in this study to start cold cracking. At the conclusion of the study, it also had one of the largest amounts of cold cracking. The cold cracking began after fewer than 2 years. The final average value was 149.6 linear in./ft^2.

The cold cracks, many of which started from the stone bruises, did not affect the reflectivity as much as they affected the reflectivity of some of the other sheeting types.

Adcolite Engineer Grade (Yellow)

Adcolite yellow sheeting also proved to be durable, but it had lower reflectivity than most of the sheetings in this study. At a −4-degree incidence angle it had a high reading of 63.6*R* and a low value of 51.6*R*, which was above specifications for new sheeting. At a +30-degree incidence angle it had a high value of 34.8*R* and a low value of 26.6*R*, which was also above specifications for new sheeting. The yellow did not fade much, as did some of the other sheetings.

The yellow Adcolite also started cold cracking early and had a large amount of cold cracking at the conclusion of the study. It started cracking after 2.2 years and had 75.3 linear in./ft at the conclusion of the study. Again, the cold cracking did not affect the reflectivity as much as it did some of the other types of sheetings. Although the numbers appeared high, the cracks were fine and did not substantially affect the reflectivity of the signs.

Fasign Engineer Grade (White)

Fasign Engineer Grade white sheeting was extremely reflective for approximately the first 4 years, but it had a short life

TABLE 3 COLD CRACKING DATA

Brand	Grade	Cold Cracking (Linear in./ft²) White	White Stone Bruised	Yellow
March 1, 1977 Test				
Adcolite	Engineer	0.0	0.0	0.0
Fasign	Engineer	0.0	0.0	0.0
Fasign	Construction	0.0	[a]	0.0
Kewalite	Engineer	[a]	[a]	[a]
Maclite	Engineer	0.0	0.0	0.0
Scotchlite	Engineer	0.0	0.0	0.0
Scotchlite	Level B	0.0	[a]	0.0
Scotchlite	Type H	0.0	[a]	0.0
Seibulite	Engineer	0.0	0.0	0.0
Toshiba	Engineer	[a]	[a]	0.0
April 20, 1983 Test				
Adcolite	Engineer	42.0	39.3	21.6
Fasign	Engineer	3.5	7.0	1.7
Fasign	Construction	4.1	[a]	0.5
Kewalite	Engineer	48.9	48.6	34.4
Maclite	Engineer	[b]	[b]	3.6
Scotchlite	Engineer	31.7	46.1	4.0
Scotchlite	Level B	[c]	[a]	5.4
Scotchlite	Type H	0.0	[a]	0.0
Seibulite	Engineer	0.0	0.0	0.0
Toshiba	Engineer	[a]	[a]	48.6
March 18, 1987 Test				
Adcolite	Engineer	149.6	124.9	75.3
Fasign	Engineer	[b]	[b]	[b]
Fasign	Construction	[b]	[a]	[b]
Kewalite	Engineer	[c]	[c]	[c]
Maclite	Engineer	[b]	[b]	[b]
Scotchlite	Engineer	130.9	177.8	45.6
Scotchlite	Level B	[c]	[a]	39.0
Scotchlite	Type H	0.4	[a]	8.7
Seibulite	Engineer	0.1	0.0	0.0
Toshiba	Engineer	[a]	[a]	[b]

[a]Not tested.
[b]Retired because of poor results.
[c]More than 224 linear in./ft².

span. It was retired in 1984 after a service life of approximately 7 years. At a −4-degree incidence angle, it had a high value of 124.9*R* and a low value of 24.8*R* when it was retired. It dropped below the usable specification range at approximately 6.5 years. At a +30-degree incidence angle it had a high value of 79.0*R* and a low value of 7.8*R* when it was retired. It dropped below the usable specification range for this angle at 7 years. Stone bruising had little effect on the reflectivity.

Cold cracking was not a big problem with the Fasign sheeting. Cold cracks could not be seen for more than 5.5 years. Cracking started in October 1982 and measured 20.7 linear in./ft² when the sheeting was retired. The cold cracking seemed to decrease the reflectivity.

Fasign Engineer Grade (Yellow)

Fasign Engineer Grade yellow sheeting did not prove to be substantially reflective or durable. At a −4-degree incidence angle, it had a high value of 79.0*R* and a low value 7.8*R*. It dropped below usable specifications in fewer than 5 years and was retired in April 1984. At a +30-degree incidence angle it had a high value of 42.7*R* and a low value of 6.4*R* when it was retired. It dropped below usable specification after 6 years. The yellow coloring faded moderately.

Cold cracking was not a problem. It began in April 1983 after 6 years of weathering. When it was retired, the sheeting had 16.1 linear in./ft² of cold cracking, which did not appear to decrease the reflectivity.

Fasign Construction Grade (White)

Fasign Construction Grade white sheeting was similar to Fasign Engineer Grade. The reflectivity and cold cracking data proved to be consistently higher than the Engineer Grade but was close. This sheeting also proved to be less durable than the other reflective sheetings tested. At a −4-degree incidence angle it had a high value of 127.2*R* and a low value of 18.1*R* when it was retired in April 1984. It dropped below usable specifications for approximately 7 years. At a +30-degree incidence angle it had a high value of 127.2*R* and a low value of 18.1*R*. It dropped below specifications for approximately 7 years.

Cold cracking was not excessive, but it did appear to affect the reflectivity. When the cold cracking began, the reflectivity dropped rapidly. It started after 6.2 years and increased to 27.6 linear in./ft.

Fasign Construction Grade (Yellow)

Fasign Construction Grade yellow sheeting performed poorly. The initial reflectivity was low compared with the other sheeting tested, and this sheeting had a short life span. For a −4-degree incidence angle it had a high value of 78.7*R* and a low value of 10.7*R* when retired in April 1984. At a +30-degree incidence angle it had a high value of 43.3*R* and a low value of 7.7*R* at retirement. It dropped below usable specifications after approximately 7 years. The yellow also faded substantially.

Cold cracking was not excessive. It began in April 1983, and when the signs were retired in 1984 cold cracks measured 7.4 linear in./ft². The cold cracking seemed to increase the loss in reflectivity.

Kewalite Engineer Grade (White)

Kewalite Engineer Grade white sheeting performed fairly well. It consistently had the highest reflectivity readings but dropped quickly after 7 years. At a −4-degree incidence angle it had a high reading of 135.7*R*, which was the highest reading of all the sheetings tested. It had a low reading of 23.6*R*. It dropped below allowable specifications after approximately 9 years. At a +30-degree incidence angle it had a high value of 84.9*R* and a low value of 12.1*R*. It dropped below usable specifications after approximately 9.5 years. Stone bruising did not seem to affect the reflectivity.

Cold cracking was substantial for the Kewalite, and it seemed to be directly related to the decrease in reflectivity. It began after 5.2 years and increased quickly to more than 224 linear in./ft^2 by the end of the test.

Kewalite Engineer Grade (Yellow)

Kewalite Engineer Grade yellow sheeting performed fairly well. It consistently had the highest reflectivity, but it dropped quickly after 7 years. It did have a few major flaws. It faded to the same color as the white sheeting after only 6 years. At a −4-degree incidence angle it had a high value of 123.6*R* and a low value of 22.4*R*. It dropped below the usable specification after 9 years. At a +30-degree incidence angle it had a high value of 68.5*R* and a low value of 13.3*R*. It dropped below usable specifications for this angle after 9 years.

Cold cracking was substantial. This sheeting had by far the highest amount of cold cracking of any of the yellow reflective sheetings. The cracking started after 6.2 years and increased quickly to more than 224 linear in./ft^2 by the conclusion of the study.

Scotchlite Level B Grade (White)

Scotchlite Level B Grade sheeting did not perform well. At a −4-degree incidence angle it had a high value of 66.6*R*, which is below specifications for new sheeting. It had a low value of 36*R* and dropped below usable specifications after approximately 4 years. At a +30-degree incidence angle it had a high value of 41.3*R* and a low value of 28.3*R*. It never dropped below usable specifications for this incidence angle.

Cold cracking was also a problem. It began after approxmately 1.7 years and quickly increased to the limit of 224 linear in./ft^2 after 5.7 years. Although the amount of cold cracking was large, the cracks were fine and did not stand out as much as they did on many of the other sheetings tested.

Scotchlite Level B Grade (Yellow)

Scotchlite Level B Grade yellow performed fairly well. Although the reflective intensity was not as high as that of many of the other sheetings, the sheeting proved to be durable and had a long life. At a −4-degree incidence angle it had a high value of 81.3*R* and a low value of 63.1*R*, which never dropped below the specifications for new sheeting. At a +30-degree incidence angle it had a high value of 57.2*R* and a low value of 24.2*R*. Fading was insignificant after 10 years of testing.

Cold cracking was not a problem. It began after 3.3 years and reached a maximum value of 39.0 linear in./ft^2 after 10 years. Cold cracking appeared to have little effect on the reflectivity of the signs.

Scotchlite Engineer Grade (White)

Scotchlite Engineer Grade white sheeting was one of the best sheetings in the study. At a −4-degree incidence angle it had a high value of 117.4*R* and a low value of 90.2*R*, which was the highest reflectivity at the end of the study. This is also 20.2*R* above specifications for new sheeting. At a +30-degree incidence angle it had a high value of 64.9*R* and a low value of 48.9*R*, which was also the highest value for white sheeting after 10 years. Stone bruising had no effect on the reflectivity, but it caused some of the worst cold cracking on these signs.

Cold cracking, which began after 1.7 years, was fairly high but did not seem to affect the reflectivity. At the conclusion of the test, the sheeting had 130.9 linear in./ft^2 of cold cracks. These cold cracks were fine but darkened and consequently stood out more.

Scotchlite Engineer Grade (Yellow)

Scotchlite Engineer Grade yellow sheeting performed fairly well. It proved to be durable, but the reflectivity was somewhat lower compared with other sheetings tested. At a −4-degree incidence angle it had a high value of 79.8*R* and a low value of 65.9*R*, which never dropped below specifications for new sheeting. At a +30-degree incidence angle it had a high value of 37.4*R* and a low value of 31.4*R*, which was also above specifications for new sheeting. A minimal amount of fading occurred.

Cold cracking, which began after approximately 3.3 years, was not a problem with this sheeting. At the conclusion of the test the sheeting showed 45.6 linear in./ft^2 of cold cracking. These cracks did not seem to affect the reflectivity because they were extremely fine.

Seibulite Engineer Grade (White)

Seibulite Engineer Grade white sheeting performed very well. It had one of the best reflective intensity ratings in the first five years. At −4-degree incidence angle it had a high value of 126.3*R* and a low value of 43.6*R*. It never dropped below specifications and finished second most reflective at 10 years of age. Stone bruising did not affect the reflectivity.

Cold cracking resistance was excellent. The sheeting almost looked like new and was by far the most resistant to cold cracking. The final appearance of the sheeting was excellent.

Seibulite Engineer Grade (Yellow)

Seibulite Engineer Grade yellow sheeting performed very well. It started out as one of the most reflective yellow sheetings in the study. At a −4-degree incidence angle it had a high value of 89.5*R* and a low value of 83.7*R*. This value never dropped below specifications for new sheeting. In fact, it never came within 30*R* of specifications for new sheeting after 10 years of testing. At a +30-degree incidence angle it had a high value of 60.4*R* and a low value of 51*R*, which is 29*R* above specifications for new sheeting.

Cold cracking was nonexistent for this sheeting. It had the least amount of cold cracking of any of the yellow sheetings.

Toshiba Engineer Grade (Yellow)

Toshiba Engineer Grade yellow sheeting performed fairly well. It was reflective for approximately 6 years and then declined quickly. At a −4-degree incidence angle it had a high value of 115.3*R*, which was the highest value for yellow sheeting. It had a low value of 18.8*R*, and it dropped below usable specifications after approximately 8 years. At a +30-degree incidence angle it had a high value of 78.6*R* and a low value of 11.6*R*. It dropped below usable specifications after 8 years and was retired after 8.2 years. Fading seemed to be a problem with this sheeting, which turned from bright yellow to light peach after only 5 years.

Cold cracking was fairly high for this sheeting. It began after approximately 5 years and increased quickly to 107.8 linear in./ft^2.

Maclite Engineer Grade (White)

Maclite Engineer Grade white sheeting started with high reflectivity but quickly dropped. At a −4-degree incidence angle it had a high reading of 128.6*R* and a low reading of 10.3*R* when it was retired in October 1982. It dropped below usable specifications after fewer than 4 years. At a +30-degree incidence angle it and a high value of 76.8*R* and a low value of 6.1*R* when it was retired. Stone bruising did not affect the reflectivity.

Cold cracking was not a problem for the first 3 years but increased dramatically thereafter. The clear coat blistered and fell off early in the test.

Maclite Engineer Grade (Yellow)

Maclite Engineer Grade yellow sheeting performed poorly. The reflectivity started out fairly high but dropped quickly. At a −4-degree incidence angle it had a high value of 85.1*R* and a low value of 2.9*R* when it was retired in 1982. At a +30-degree incidence angle it had a high value of 76.4*R* and a low value of 3.7*R* when it was retired. It dropped below specifications for usable sheeting in fewer than 4 years and was the worst yellow reflective sheeting in the test.

Although the numbers for cold cracking were low, they did not show the problems with this sheeting. Fifty percent of the clear covering on the face of the sheeting had blistered and peeled off by 1979; 80 percent did so by 1982. Cold cracking began after 6 years and increased to a maximum value of 40.6 linear in./ft^2 when the sheeting was retired in 1984.

Scotchlite Type H Grade (White)

Scotchlite Type H white sheeting had very high reflectivity. At a −4-degree incidence angle it had a high value of 307.7*R* and a low value of 243.9*R*. It dropped below specifications for new sheeting after approximately 9 years but never dropped below specifications for usable sheeting. At a +30-degree incidence angle it had a high value of 223.3*R* and a low value of 139.9*R*, which is above specifications for new sheeting.

Cold cracking was almost nonexistent, with only 0.4 linear in./ft^2 after 10 years of testing. Overall, this sheeting was excellent. This sheeting cannot be compared with the other sheetings in this test because it is a Type H sheeting and not a standard or engineering grade.

Scotchlite Type H Grade (Yellow)

Scotchlite Type H yellow sheeting was very reflective. At a −4-degree incidence angle it had a high value of 230.8*R* and a low value of 165.2*R*, which was above specifications for new sheeting. At a +30-degree incidence angle it had a high value of 199.5*R* and a low value of 149.1*R*, which was also above specifications for new sheeting.

Hardly any cold cracking was present in this sheeting; the few cold cracks that did occur were barely visible.

CONCLUSIONS

At the end of the 10-year study the white sheetings had the following average reflective intensities at an incidence angle of −4 degrees:

- Adcolite Engineer Grade: 73.6*R*,
- Fasign Engineer Grade: retired in 1984,
- Fasign Construction Grade: retired in 1984,
- Kewalite Engineer Grade: 23.6*R*,
- Maclite Engineer Grade: retired in 1982,
- Scotchlite Engineer Grade: 90.2*R*,
- Scotchlite Level B: 36.0*R*,
- Scotchlite Type H: 243.9*R*,
- Seibulite Engineer Grade: 43.6*R*, and
- Toshiba Engineer Grade: not tested.

The reflective intensities for the following white sheetings were high: Scotchlite Type "H," Scotchlite Engineer Grade, Adcolite Engineer Grade, and Seibulite Engineer Grade. The reflective intensities for Fasign Engineer Grade, Fasign Construction Grade, and Maclite-Engineer Grade were extremely low, and consequently the sheetings were retired before the end of the test period.

At the end of the 10-year study, the yellow sheetings had the following average reflective intensities at an incidence angle of −4 degrees:

- Adcolite Engineer Grade: 51.6*R*,
- Fasign Engineer Grade: retired in 1984,
- Fasign Construction Grade: retired in 1984,
- Kewalite Engineer Grade: 22.4*R*,
- Maclite Engineer Grade: retired in 1982,
- Scotchlite Engineer Grade: 65.9*R*,
- Scotchlite Level B: 63.1*R*,
- Scotchlite Type H: 165.2*R*,
- Seibulite Engineer Grade: 84.4*R*, and
- Toshiba Engineer Grade: not tested.

The reflective intensities for the following yellow sheetings were high: Scotchlite Type "H," Seibulite Engineer Grade, and Scotchlite Engineer Grade. Fasign Engineer Grade, Fasign Construction Grade, Maclite Engineer Grade, and Toshiba Engineer Grade sheetings were retired because of poor reflectivity and fading color.

At the end of the study cold-cracking measurements for the white reflective sheetings were as follows:

- Adcolite Engineer Grade: 149.6 linear in./ft^2,
- Fasign Engineer Grade: retired because of poor results,

- Fasign Construction Grade: retired because of poor results,
- Kewalite Engineer Grade: excessive cold cracking,
- Maclite Engineer Grade: retired because of poor results,
- Scotchlite Engineer Grade: 130.9 linear in./ft^2,
- Scotchlite Level B: excessive cold cracking,
- Scotchlite Type H: 0.4 linear in./ft^2,
- Seibulite Engineer Grade: 0.1 linear in./ft^2, and
- Toshiba Engineer Grade: not tested.

Seibulite Engineer Grade and Scotchlite Type H sheeting had virtually no cold cracking. The rest of the sheetings were susceptible to cold cracking and cracked severely.

At the end of the study the cold-cracking measurements for the yellow sheetings were as follows:

- Adcolite Engineer Grade: 75.3 linear in./ft^2,
- Fasign Engineer Grade: retired because of poor results,
- Fasign Construction: retired because of poor results,
- Kewalite Engineer Grade: excessive cold cracking,
- Maclite Engineer Grade: retired because of poor results,
- Scotchlite Engineer Grade: 45.6 linear in./ft^2,
- Scotchlite Level B: 39.0 linear in./ft^2,
- Scotchlite Type H: 8.7 linear in./ft^2,
- Seibulite Engineer Grade: 0 linear in./ft^2, and
- Toshiba Engineer Grade: retired because of poor results.

The Seibulite Engineer Grade and Scotchlite Type H yellow sheetings showed virtually no cold cracking. The rest of the sheetings were susceptible to cold cracking and cracked severely.

Stone bruised white sheeting did not have significant increased cold cracking when compared with non-stone-bruised white sheeting. The reflectivity of white stone-bruised sheeting was almost the same as the white non-stone-bruised sheetings.

RECOMMENDATIONS

On the basis of the 10-year evaluation of reflective sheetings, the following recommendations appear to be warranted: Scotchlite Type H, Scotchlite Engineer Grade, and Seibulite Engineer Grade sheetings are recommended for high reflectivity, minimal cold cracking, and durability. Fasign Engineer Grade, Fasign Construction Grade, Maclite Engineer Grade, and Toshiba Engineer Grade sheeting should not be used because of poor reflectivity, excessive cold cracking, and shorter life.

Luminance Measurements of Retroreflective Warning Signs at Night Using the CapCalc System

Helmut T. Zwahlen, Qi Li, and Jing Yu

A study to measure the luminance of traffic signs at night with no appreciable glare sources within the field of view at certain distances and lateral positions ahead of a car was conducted on an unused airport runway by using CapCalc, a new photometric measuring and analysis system. Yellow warning signs for curves and turns and yellow chevron signs were placed on the right or left side of a simulated straight, level, dry, two-lane rural highway. Three different types of yellow sheeting materials (enclosed lens, encapsulated lens, and prismatic sheeting) with different reflectance values were used. The results of this study confirmed that the luminance of a reflective traffic sign observed by a driver at night illuminated by the beams of the car is not a constant but changes according to an inverted U-shaped function as the distance between the car and the traffic sign ahead is increased. The observed luminance first increases with the distance between the car and the traffic sign ahead until about 400 ft and then decreases. The highest luminance values for the different lateral positions of the signs (right or left side of the road) are quite different; however, the patterns of the luminance curves as a function of the distance for the right side and the left side traffic signs are similar. Improvements to CapCalc hardware are suggested.

Retroreflective materials are used to enable drivers to more easily detect and recognize signs, delineation elements, and other reflectorized traffic control elements at night under headlamp illumination. Early detection and recognition are important factors in a driver's hazard avoidance process (*1*). The process suggested for the avoidance of an object on the highway can be used to analogously describe a driver's response to a reflectorized traffic sign and other reflectorized devices that warn a driver of a potentially dangerous road condition ahead at night.

The detection and recognition distances for traffic signs and devices at night are determined by various factors, such as size, color, shape, background, weather conditions, and the luminance of the sign. The *Manual On Uniform Traffic Control Devices* (MUTCD) (*2*) contains specifications and recommendations for size, color, symbols used, and shape for most signs and devices in service. Another important and controllable factor for the detection or recognition distance is the luminance of a sign or a device. MUTCD indicates that the sign or device should be retroreflectorized or be illuminated at night. It does not contain a requirement for a minimal luminance value for a particular sign or group of signs or for a particular device or group of devices.

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The luminance of a sign is determined by the retroreflectance of the material; the relative positions of the headlamps, the sign, and the driver's eyes; the intensity distribution of the headlamps; and the headlamp misaim. Woltman and Szczech (*3*) proposed the use of luminance as a criterion for evaluating performance of signs (instead of retroreflectance) because the luminance provides a means to more directly match driver needs. A study by Sivak and Olson in 1983 (*4*) determined luminance as a function of the driver needs for nighttime sign recognition, and an optimal luminance of 75 cd/m^2 was proposed.

Mace et al. (*5*) investigated the minimal luminance requirements for official highway signs in 1986. They pointed out two reasons for the lack of a standard to reflect the fundamental driver needs for luminance. The first is the absence of conclusive performance data to support a minimal luminance standard; the second is that there is no practical and reliable way of measuring luminance in the field. (The lack of the proper means of measuring luminance in the field is probably also the major reason for the absence of supporting data.)

In the field, the luminance measurement method using a traditional photometer (e.g., Pritchard photometer) is expensive, inconvenient, and slow. The smallest aperture or measuring angle for a photometer is usually 2 min of arc. For example, if a target is placed 900 ft away from the photometer, the 2 min of arc aperture is used, and only 60 percent of the total circular target area is used to measure the luminance (circular center portion of target). The diameter of the target area for a reliable measurement must be larger than 0.675 ft (8.2 in.). It is therefore difficult to measure the luminances at one or more places on a warning sign that is placed relatively far away from the photometer and that is virtually covered by a large black symbol or message. To overcome these problems and to provide faster measurements, a new photometric measuring and analysis system—CapCalc (Capture an image and Calculate photometric values)—was developed by the Canadian National Research Council (NRCC).

The primary objective of this study was to measure and analyze the luminance of traffic signs in the field under low- and high-beam illumination at night as a function of the distance between the car and sign while using and evaluating the newly developed CapCalc system. Another objective was to examine the luminance performance for signs with different sheeting materials, such as enclosed lens, encapsulated lens, and micro-prismatic sheeting, for different distances of the signs ahead, for high and low beams, and for different lateral positions (left and right sides of the road). In addition, measurements with a Pritchard photometer were made for comparison purposes.

EXPERIMENTAL SITE AND APPARATUS

This study was conducted on a 1,500- × 75-ft unused, level, concrete airport runway near Athens, Ohio. The stationary experimental vehicle containing the CapCalc system and the retroreflective traffic signs were arranged to simulate a two-lane rural highway (Figure 1). To reduce the experimental effort, three similar signs were spaced 300 ft apart and 16 ft away from the longitudinal center line of the experimental vehicle to the right side or 22 ft away from the longitudinal center line of the experimental vehicle to the left side. The selected lateral positions of the signs represent conditions found along two-lane rural highways. The bottoms of the signs were 6 ft above the ground. The vehicle used in this experiment was a 1981 Volkswagen Rabbit with properly aimed H6054 headlamps (12.8 to 13 V idle operating voltage, hottest point of the right and left low beams approximately 2 degrees to the right and approximately 2 degrees downward, and hottest point of the right and left high beams approximately 0 degrees vertical and 0 degrees horizontal). The car was placed at four positions 75 to 300 ft from the nearest sign, with an increment of 75 ft between each position. The longitudinal axis of the car was always parallel to the runway axis.

CapCalc, the new computer-based luminance-measuring and image analysis system used in this study, was initially developed by NRCC and is manufactured and marketed by MSR Scientific Enterprises in Ottawa, Canada. The system used in this study consists of a V-lambda corrected solid-state video camera (Burle CCD), a minimonitor, an image processing board, and a portable personal computer with a hard disk. The system is powered by a 12 V DC/110 V, 60 Hz AC inverter that is powered by the car's electrical system (battery) while collecting the data in the field. The Burle CCD camera of the CapCalc system was placed in the driver's seat of the car in such a way that the center of the front of the lens was approximately at the position at which a driver's eyes would be. The computer and minimonitor were placed in the back seat near the passenger side door to provide easy access to the keyboard and the monitor (Figure 2).

The signs used in this study had three types of retroreflective sheeting materials. Three 30- × 30-in. yellow curve or turn warning signs with enclosed lens sheeting were used, with an average specific intensity per unit area (SIA) (SIA, 0.2 degrees observation angle and −4 degrees entrance angle) of 92.0 cd/lux/m^2 for Sign 1 (measured at 75, 150, 225, and 300 ft), an average SIA of 91.4 cd/lux/m^2 for Sign 2 (measured at 375, 450, 525, and 600 ft), and 86.0 cd/lux/m^2 for Sign 3 (measured at 675, 750, 825, and 900 ft). Three 36- × 30-in. yellow chevron signs with encapsulated lens sheeting were used, with an average SIA of 265.1 cd/lux/m^2 for Sign 1, 263.2 cd/lux/m^2 for Sign 2, and 279.2 cd/lux/m^2 for Sign 3. Three 30- × 30-in. yellow curve and turn warning signs with microprismatic sheeting were used, with an average SIA of 957.6 cd/lux/m^2 for Sign 1, 1041.2 cd/lux/m^2 for Sign 2, and 1053.7 cd/lux/m^2 for Sign 3 (Figure 3).

MEASUREMENT METHOD

The study was conducted several nights between 7:30 and 10:00 p.m. During the measurements, the sky was clear or slightly cloudy. The concrete surface of the runway was dry.

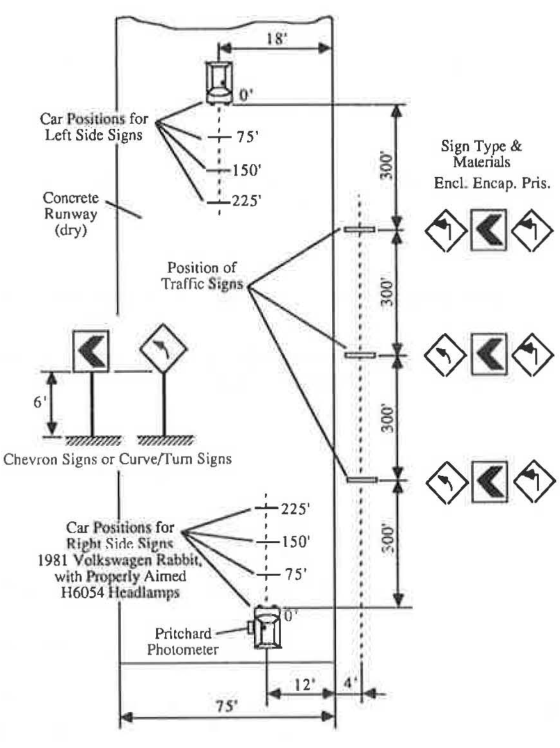


FIGURE 1 Layout of experimental site.

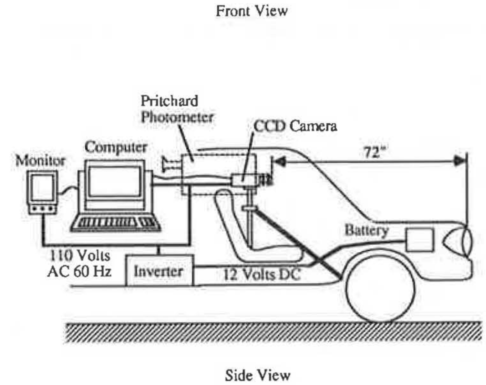


FIGURE 2 Arrangement of CapCalc system in experimental car.

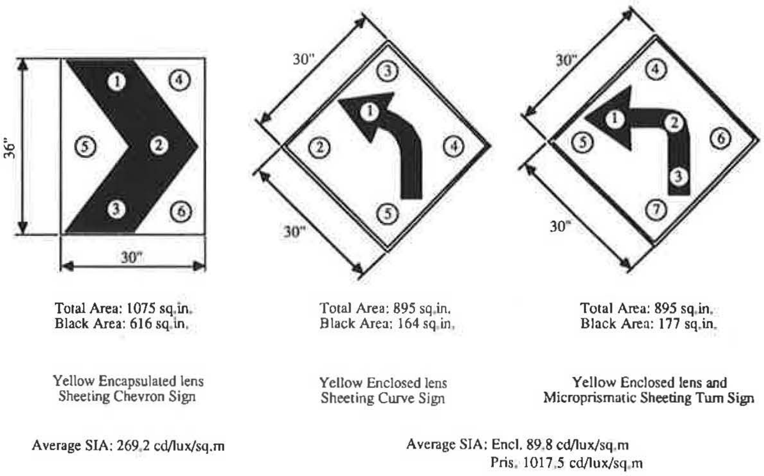


FIGURE 3 Dimensions and average SIAs of retroreflective materials of signs (circled numbers indicate approximate measurement positions for Pritchard photometer and CapCalc comparisons).

The temperature was between 36 and 43°F. Three signs with the same retroreflective sheeting material were mounted on the steel posts in such a way that the surfaces of the signs were approximately perpendicular to the longitudinal axis of the car.

Three signs were used to increase the speed of the data collection process and to minimize the movement and alignment of the experimental vehicle. CapCalc was used to measure the luminances of the entire picture containing the three signs under low- and high-beam illumination at 300, 225, 150, and 75 ft (measured from the first sign to the headlamps of the car). Using three equally spaced signs also provided luminance values for 600, 525, 450, and 375 ft and for 900, 825, 750, and 675 ft. Thus, for each reflective sheeting material, low beams or high beams, signs on the left or right side of the roadway, a set of luminance measurements for 12 sign positions (using an increment of 75 ft between each sign position) was obtained for further analysis. A zoom setting of 75 mm was used for the 300- and 225-ft measurements, (distance setting at infinity, lens 2 (LB) and 5.6 (HB) for enclosed and encapsulated lenses, lens 4 (LB) and 8 (HB) for prismatic lens). A zoom setting of 50 mm was used for the 150-ft measurements (distance setting at infinity, lens 2.8 (LB) and 5.6 (HB) for enclosed lens, 2 (LB) and 5.6 (HB) for encapsulated lens, 5.6 (LB) and 11 (HB) for prismatic lens). A zoom setting of 30 mm was used for the 75-ft measurements (distance setting at infinity, lens 2.8 (LB) and 5.6 (HB) for enclosed lens, 2 (LB) and 4 (HB) for encapsulated lens, 5.6 (LB) and 8 (HB) for prismatic lens).

The pictures taken with CapCalc are stored as a luminance value matrix containing 245,760 pixel values (512 × 480). To obtain accurate luminance values, zeroing was performed before each measurement. Zeroing, as used here, means to have the CapCalc system take a number of black pictures and average these values to obtain an average zero, or black, level for each pixel. In this study the number was eight to obtain more stable and accurate values. With this zero level recorded, CapCalc was then instructed to take and average eight pictures of the image of interest. All images of interest can be saved on a diskette or hard disk for further reference or for further luminance and contrast analyses.

The analysis software in the CapCalc system is menu driven and user friendly. Luminance values of reflectorized objects such as traffic signs can be obtained in three different ways. First, CapCalc can display the luminance value of any single pixel within the picture under the Relative Visual Performance (RVP) menu. The user simply selects the Luminances function from the RVP menu. After the selection a crosshair (which is movable in both directions) will appear on the image screen, the corresponding x-y pixel position and the luminance value for this pixel will be displayed on the computer screen. Second, the average luminance within a measured field can be obtained by using the CapCalc the same way as a standard photometer under the Photometry menu. In this situation the user can move a rectangular frame to define a field or area of interest. The user may relocate and resize the frame, and then get the average luminance value for the pixels contained within that frame. The last and most powerful method uses the RVP calculations under the Calculate menu. To calculate the RVP, the user first defines a frame to contain the target to be analyzed. To identify the target area and background area, the user uses the Contour function to separate the luminance values of all pixels contained in the frame into several levels or equal width frequency classes. CapCalc then uses different gray levels to display the luminances that correspond to the average luminance value for each level or frequency class. The number of contours selected depends on how easily one can separate the target area from the background area. These levels can then be combined stepwise into wider and wider frequency classes until either the whole target area or the whole background area is included. After the target area and the background area are defined, the corresponding average target luminance and the average background luminance will be shown on the screen of the computer. Unfortunately, the current CapCalc software does not provide the number of pixels that are used to calculate the average luminance of each contour frequency class, information that would be useful.

In this study, because of the interest in the average luminances of the traffic signs with different retroreflective materials, the RVP calculation option was used to successfully determine the average luminance values under low- or high-beam illumination for a warning sign placed on the right or left side of the road.

RESULTS

Average luminance values of the signs under the H6054 low- or high-beam illumination, for signs placed on either side of the roadway are presented in Tables 1 and 2. The curves shown in Figures 4–7 plot the values given in Tables 1 and 2 as a function of the distance between the car's headlamps and the sign. To check the repeatability of the CapCalc system, the measurements for the signs placed on the right side of the roadway were measured again several days after the first measurements were taken. Figures 4 and 6 show that the results of the repeated measurements (dotted lines) are close to the results of the first measurement, and the CapCalc system appears to produce reasonable repeatability under field conditions. A major portion of the observed differences is most likely a result of small changes in the alignment of the longitudinal car axis and small changes in the operating voltage of the electrical system of the car. The results of the first measurement also show that under low-beam illumination, the maximum luminance value occurred between 400 and 500 ft for signs on the right side of the roadway and between 300 and 600 ft for signs on the left. Under high-beam illumination, the maximum luminance value occurred at 400 ft for signs placed on the right side of the roadway and between 450 and 600 ft for signs placed on the left side.

All shapes of the curves shown in Figures 4–7 are fairly similar to the curves shown by Woltman et al. (*3*), but the right-hand tail of each curve for the longer distances was not

TABLE 1 AVERAGE LUMINANCE VALUES FOR SIGNS ON RIGHT SIDE OF ROADWAY UNDER LOW- AND HIGH-BEAM ILLUMINATION AS A FUNCTION OF CAR-TO-SIGN DISTANCE

Car to Sign Distance (ft)	Average Luminance Values of the Signs (cd/m ^{2})					
	Encl.LB	Encl.HB	Enca.LB	Enca.HB	Pris.LB	Pris.HB
75	2.19	7.6	1.70	11.54	V.L.	V.L.
150	3.79	34.68	5.20	60.64	11.47	45.42
225	7.09	80.64	7.09	230.55	53.68	435.60
300	14.17	114.14	55.51	213.89	125.80	899.78
375	24.77*	119.25*	64.20*	251.55	194.51	1174.28*
450	23.73	89.76	51.33	305.47*	297.83*	1065.22
525	21.87	70.56	51.13	220.01	267.17	726.00
600	18.17	57.07	42.37	127.05	217.90	606.69
675	10.93	46.30	36.78	122.49	144.45	625.02
750	10.78	42.24	20.25	104.70	133.51	450.67
825	6.84	30.24	13.88	91.27	160.83	363.00
900	7.79	25.94	15.61	54.45	103.76	326.70
Overall Average	12.65	59.87	30.42	149.47	155.53	610.76

NOTE: Encl. = enclosed lens; Enca. = encapsulated lens; Pris. = prismatic sheeting.
* Maximum Luminance.
V.L. Very low luminance value. It was too low for CapCalc to measure.

TABLE 2 AVERAGE LUMINANCE VALUES FOR SIGNS ON LEFT SIDE OF ROADWAY UNDER LOW- AND HIGH-BEAM ILLUMINATION AS A FUNCTION OF CAR-TO-SIGN DISTANCE

Car to Sign Distance (ft)	Average Luminance Value of the Signs (cd/m ^{2})					
	Encl.LB	Encl.HB	Enca.LB	Enca.HB	Pris.LB	Pris.HB
75	0.87	7.05	0.92	7.41	V.L.	V.L.
150	1.64	24.89	2.44	31.66	4.41	45.18
225	2.93	28.56	7.11	62.26	15.04	108.90
300	4.36*	35.54	9.57*	88.20	19.14	181.44
375	4.01	33.67	8.32	72.60	22.58	242.33
450	2.51	29.04	8.64	84.42	24.89	318.37
525	3.72	36.34	9.24	119.32*	25.97	308.55
600	3.97	38.76*	9.57*	114.14	30.07*	322.56*
675	2.46	22.45	4.93	59.16	17.48	204.63
750	1.89	19.36	5.75	55.40	19.36	256.75
825	2.66	23.36	6.40	77.82	19.14	163.35
900	3.19	21.87	5.44	62.26	19.14	171.36
Overall Average	2.85	26.74	6.53	69.55	19.77	211.22

NOTE: Encl. = enclosed lens; Enca. = encapsulated lens; Pris. = prismatic sheeting.
* Maximum luminance.
V.L. Very low luminance value. It was too low for CapCalc to measure.

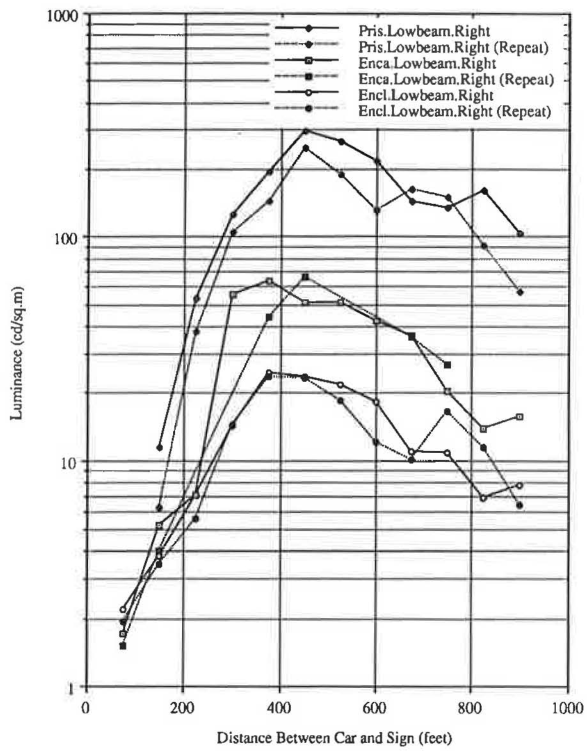


FIGURE 4 Luminance values for retroreflective sheeting materials versus distance between car and sign for signs on right side of roadway under low-beam illumination, including repeat measurements.

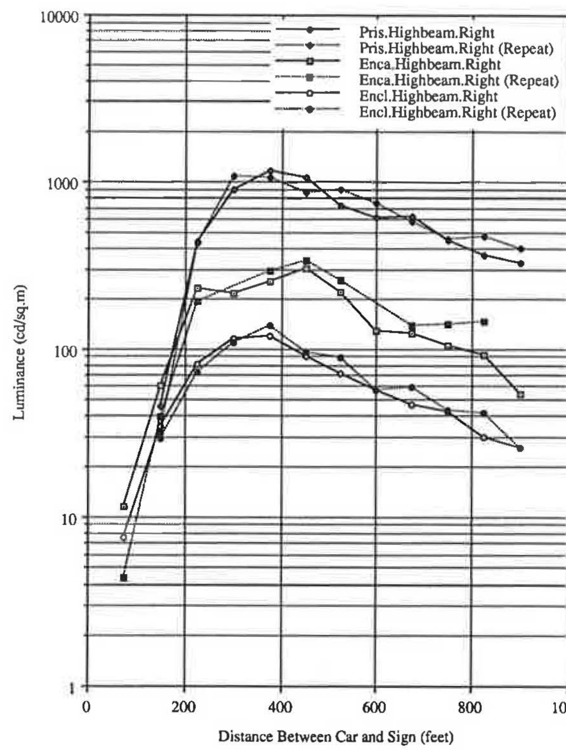


FIGURE 6 Luminance values for retroreflective sheeting materials versus distance between car and sign for signs on right side of roadway under high-beam illumination, including repeat measurements.

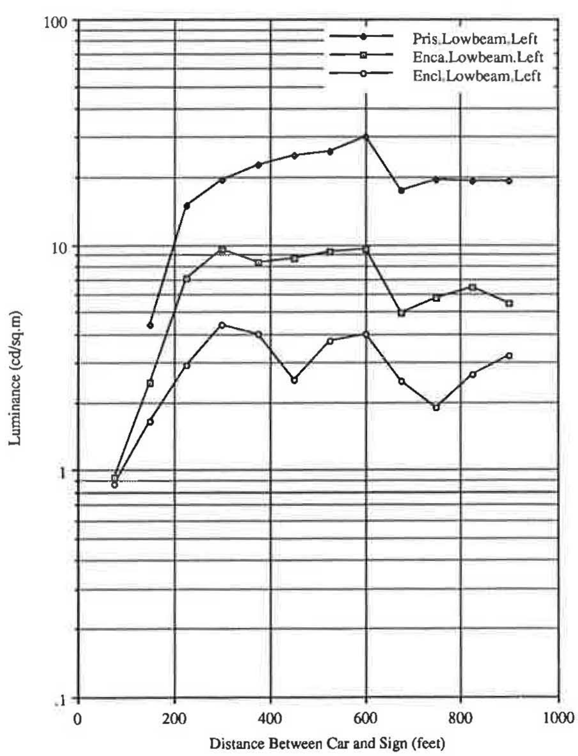


FIGURE 5 Luminance values for retroreflective sheeting materials versus distance between car and sign for signs on left side of roadway under low-beam illumination.

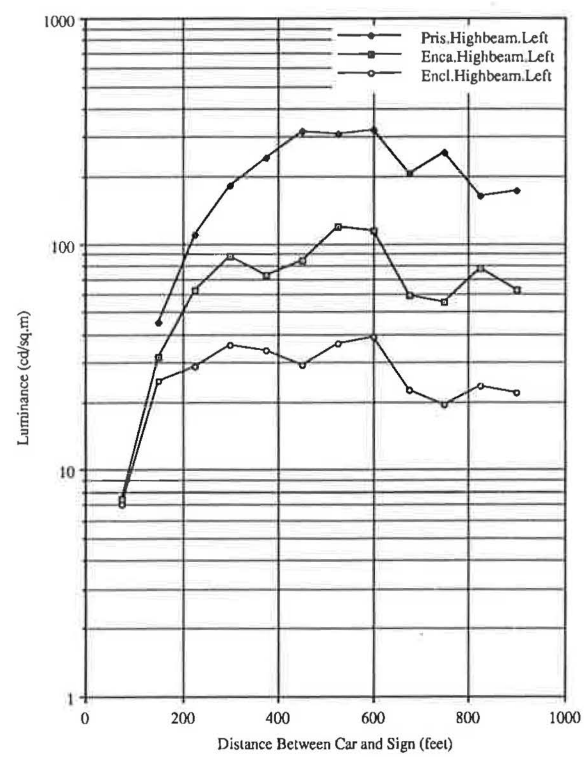


FIGURE 7 Luminance values for retroreflective sheeting materials versus distance between car and sign for signs on left side of roadway under high-beam illumination.

as smooth as expected. The major reason may be because in this study three similar signs were captured and measured in one CapCalc picture to reduce the number of pictures taken and to increase the speed of the data collection process. When the distance of the car to the first sign was 75 ft, to contain all the three signs within one scene, the zoom had to be set at 30 mm for signs on the right and 20 mm for signs on the left side of the roadway. The image area covered by the third sign (at 675 ft) became small and contained only 20 to 50 pixels. With such a small number of pixels, it was difficult to identify the target areas and the background areas accurately in the CapCalc pictures by using the Contour function; therefore, the calculated average luminance values for the 675, 750, 825, and 900 ft distances are not as accurate as the values for the shorter distance and show more variability.

Figures 4–7 also show differences in the luminances because of the different beam illumination and sheeting material types. For comparison, the ratio of luminances under high-beam illumination to that under low-beam illumination for the same sheeting material and the ratio of the luminances for the different sheeting materials under the same beam illumination are shown in Tables 3 and 4 for signs placed on either side of the roadway. The average ratios (averaged over all car to sign distances) for the luminances between high- and low-beam illumination are 4.31 to 7.55 for the three types of retroreflective sheeting materials for signs on the right side of the roadway and 9.64 to 10.63 for the three types of retroreflective sheeting materials for signs on the left. The average ratio for the luminances (averaged over all distances from 75 to 900 ft) between the prismatic sheeting and the enclosed lens sheeting was 11.5 for low-beam illumination and 9.64 for high-beam illumination for signs placed on the right side of the roadway. For signs on the left side, the average ratio was 6.93 for low-beam illumination and 7.54 for high-

TABLE 3 RATIOS OF LUMINANCE VALUES FOR SIGNS ON RIGHT SIDE OF ROADWAY

Car to Sign Distance (ft.)	Ratio of HB Lumi. to LB Lumi. for the Same Retroreflective Material			Ratio of the Luminances for the Different Retroreflective Materials under the Same Beam Illumination					
	Encl. HB/LB	Enca. HB/LB	Pris. HB/LB	Enca/Encl LB	Enca/Encl HB	Pris/Encl LB	Pris/Encl HB	Pris/Enca LB	Pris/Enca HB
75	3.47	6.79	N.D.	0.78	1.52	N.D.	N.D.	N.D.	N.D.
150	9.15	11.66	3.96	1.37	1.75	3.03	1.31	2.21	0.75
225	11.37 *	32.52 *	8.11 *	1.0	2.86	7.57	5.40	7.57	1.89
300	8.06	3.85	7.15	3.92 *	1.87	8.88	7.88	2.27	4.21
375	4.81	3.92	6.04	2.59	2.11	7.85	9.85	3.03	4.67
450	3.78	5.95	3.58	2.16	3.40 *	12.55	11.87	5.80	3.49
525	3.23	4.30	2.72	2.34	3.12	12.22	10.29	5.23	3.30
600	3.14	3.00	2.78	2.33	2.23	11.99	10.63	5.14	4.78
675	4.24	3.33	4.33	3.37	2.65	13.22	13.50 *	3.93	5.10
750	3.92	5.17	3.38	1.88	2.48	12.38	10.67	6.59	4.30
825	4.42	6.58	2.26	2.03	3.02	23.51 *	12.00	11.59 *	3.98
900	3.33	3.49	3.15	2.0	2.10	13.32	12.59	6.65	6.00 *
Average	5.17	7.55	4.31	2.15	2.43	11.5	9.64	5.46	3.86

NOTE: Encl. = enclosed lens; Enca. = encapsulated lens; Pris. = prismatic sheeting.
* Maximum ratio
N.D. No data

TABLE 4 RATIOS OF LUMINANCE VALUES FOR SIGNS ON LEFT SIDE OF ROADWAY

Car to Sign Distance (ft.)	Ratio of HB Lumi. to LB Lumi. for the Same Retroreflective Material			Ratio of the Luminances for the Different Retroreflective Materials under the Same Beam Illumination					
	Encl. HB/LB	Enca. HB/LB	Pris. HB/LB	Enca/Encl LB	Enca/Encl HB	Pris/Encl LB	Pris/Encl HB	Pris/Enca LB	Pris/Enca HB
75	8.10	8.05	N.D.	1.06	1.05	N.D.	N.D.	N.D.	N.D.
150	15.18*	12.98*	10.24	1.49	1.27	2.69	1.82	1.81	1.43
225	9.75	8.76	7.24	2.43	2.18	5.13	3.81	2.12	1.75
300	8.15	9.22	9.35	2.19	2.48	4.45	5.11	2.03	2.06
375	8.40	8.73	10.73	2.07	2.16	5.63	7.20	2.71	3.34
450	11.57	9.77	12.79	3.44*	2.91	9.92	10.96	2.88	3.77
525	9.77	12.91	11.88	2.48	3.28	6.98	8.49	2.81	2.59
600	9.76	11.93	10.73	2.41	2.94	7.57	8.32	3.14	2.83
675	9.13	12.00	11.71	2.00	2.64	7.11	9.11	3.55*	3.46
750	10.24	9.63	13.26*	3.04	2.86	10.24*	13.26*	3.37	4.63*
825	8.78	12.16	8.53	2.41	3.33*	7.20	6.99	2.99	2.10
900	6.86	11.44	8.95	1.71	2.85	6.00	7.84	3.52	2.75
Average	9.64	10.63	10.49	2.23	2.50	6.93	7.54	2.81	2.79

NOTE: Encl. = enclosed lens; Enca. = encapsulated lens; Pris. = prismatic sheeting.
* Maximum ratio
N.D. No data

beam illumination. The average ratio for the luminances between the prismatic sheeting and the encapsulated lens sheeting for signs on the right side of the roadway was 5.46 for low-beam illumination and 3.86 for high-beam illumination. For signs on the left side of the roadway the ratio was 2.81 for low-beam illumination and 2.79 for high-beam illumination. The average ratio for the luminances between the encapsulated lens sheeting and enclosed lens sheeting for signs on the right side of the roadway was 2.15 for low-beam illumination and 2.43 for high-beam illumination. For signs on the left side of the roadway the ratio was 2.23 for low-beam illumination and 2.50 for high-beam illumination.

Under low-beam illumination for signs placed from 75 to 900 ft on the right side of the roadway the average luminance values were about 4.44 to 7.87 (12.65/2.85 = 4.44, 30.42/6.53 = 4.66, 155.53/19.77 = 7.87) times higher than that for signs correspondingly placed on the left side of the roadway. Under high-beam illumination for signs placed from 75 to 900 ft on the right side of the roadway the average luminance values were about 2.15 to 2.89 (59.87/26.74 = 2.24, 149.47/69.55 = 2.15, 610.76/211.22 = 2.89) times higher than that for signs correspondingly placed on the left side of the roadway.

Another important feature shown in Figures 4–7 is the substantial increase of the luminance values (for the shorter distances between the car and sign) for the prismatic sheeting material, which is much steeper than that for the enclosed lens sheeting material or the encapsulated lens sheeting material. For example, for signs with prismatic sheeting material on the right side of the roadway under low-beam illumination, the maximum luminance value occurring at 450 ft (297.83 cd/m^2) was 26 times higher than the luminance value at 150 ft (11.47 cd/m^2). The corresponding increase in luminance was only 6.5 times for the enclosed lens sheeting material. (The maximum value, 24.77 cd/m^2, occurred at 375 ft; the luminance value at 150 ft was 3.79 cd/m^2.) The corresponding increase in luminance was 12.3 times for the encapsulated lens sheeting material. (The maximum value, 64.20 cd/m^2, occurred at 375 ft; the luminance value at 150 ft was 5.20 cd/m^2.)

To check the validity of the CapCalc measurements, a Pritchard photometer was used to measure the luminance values of the signs when the second set of CapCalc measurements were made. Because the size of the Pritchard photometer is too big to fit easily inside the car so that the lens position coincided with driver's eye position, the photometer was placed outside the car (Figures 1 and 2) as close to the driver's eye position as possible. The distances between the Pritchard photometer and the traffic sign were 225 or 300 ft. Some Pritchard photometer measurements were made using the photopic filter (to compare with CapCalc, which also has a photopic filter) and some using the scotopic filter, because night driving might involve luminance conditions that require photopic, mesopic, and possibly even scotopic vision. Table 5 presents the comparison of the luminance values measured by the Pritchard photometer and the second set of corresponding measurements made using the CapCalc system. The locations on the sign for the Pritchard measurements are shown in Figure 3. The Pritchard photometer provides in some cases both photopic and scotopic measurements; however, for comparison with the CapCalc measurements only the photopic measurements should be used. The CapCalc measurements for the positions within the yellow reflective sheeting area are close and slightly lower than the corresponding Pritchard photopic measurements (Table 5). Note that the photopic CapCalc averages are based on somewhat larger areas than the Pritchard photopic values, which may be the reason for the few and rather small differences in the opposite direction (see the last two columns in Table 5). In addition, the idling car engine produced small vibrations that were conducted through the car and seat to the CapCalc camera, which could have produced some slight measurement errors. In general one would expect somewhat lower CapCalc values as a result of transmission losses caused by the windshield of the vehicle. Most CapCalc measurements for the positions within the black arrow or the black chevron area are higher than the corresponding Pritchard photopic measurements. This is most likely a result of the radiating edge effect of the yellow area, because a larger region of the black area was used for the CapCalc analysis when compared with the actual area covered by the aperture of the Pritchard. In this study, the selected CapCalc areas for each black measurement position almost included the whole area of the black arrow to fit the minimum 9- × 9-pixel rectangle inside the black area and to obtain average luminance values using the CapCalc luminance measurement function. In general the luminance values for the yellow area measured with the scotopic filter of the Pritchard photometer were somewhat lower than the corresponding values using the photopic filter.

TABLE 5 COMPARISON OF AVERAGE LUMINANCE VALUES MEASURED WITH PRITCHARD PHOTOMETER AND CAPCALC

T.o.W. Sign	S. Material	C-S.Distance	M.Position	Lowbeam: Pritchard Scoto. Filter	Lowbeam: Pritchard Photo. Filter	Lowbeam: CapCalc Photo. Filter	Highbeam: Pritchard Scoto. Filter	Highbeam: Pritchard Photo. Filter	Highbeam: CapCalc Photo. Filter	No. of Pixels Covered and Angles: by Pritchard Circle	No. of Pixels Covered and Angles: by CapCalc Rectangle
Curve Warning	Enclosed Lens	300 feet	1 (black)	N.M.	0.17	0.90	N.M.	1.07	7.46		
			2	N.M.	17.96	14.43	N.M.	110.20	109.68	10	81
			3	N.M.	14.88	10.95	N.M.	113.86	111.30		
			4	N.M.	18.31	16.05	N.M.	111.69	112.11	2' Circle	4.75' V* 5.70' H*
			5	N.M.	24.76	23.56	N.M.	109.52	118.51		
Chevron Warning	Encapsulated Lens	225 feet	1 (black)	2.11	2.05	1.61	21.60	16.91	7.21		
			2 (black)	0.09	0.09	0.27	0.63	0.43	2.03	60	120
			3 (black)	0.08	0.07	0.22	0.73	0.45	1.95		
			4	13.75	20.35	18.38	168.67	228.06	226.89	6' Circle	6.10' V 9.18' H
			5	10.34	19.86	14.78	140.69	251.13	202.17		
			6	15.14	29.29	23.02	131.10	241.88	191.51		
Turn Warning	Microprismatic	225 feet	1 (black)	0.15	0.13	0.97	1.77	1.55	11.50		
			2 (black)	0.25	0.20	N.M.	2.84	1.80	N.M.	10	81
			3 (black)	0.22	0.21	N.M.	1.18	1.46	N.M.		
			4	18.11	26.39	24.99	259.11	438.53	386.82	2' Circle	5.53' V 6.77' H
			5	27.15	41.32	40.04	309.03	553.98	524.95		
			6	23.92	38.52	35.33	223.83	435.44	418.95		
			7	40.04	72.97	60.19	294.75	508.99	531.88		

NOTE: Luminance values are in candelas per square meter.

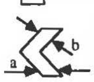
T.o.W.Sign = Type of Warning Sign S. Material = Sheeting Material

C-S. Distance = Car - Sign Distance M. Position = Measurement Position

Scoto. = Scotopic Photo. = Photopic N.M. = Not Measured.

◩ M. Position in black area ☐ M. Position in yellow area

Visual angle of a at 225 ft. is 5.4 min. of arc at 300 ft. is 4.1 min. of arc



Visual angle of a at 225 ft. is 17.8 min. of arc visual angle of b at 225 ft. is 14.0 min. of arc

* Smallest possible rectangle provided by CapCalc Luminance Function contains 9 x 9 pixels (or roughly 4.75'V x 5.70'H visual angle for a zoom setting of 75 mm).

CONCLUSIONS

This study demonstrated that obtaining luminance measurements of reflectorized traffic signs from a stationary vehicle under static conditions in the field at night with no appreciable glare sources within the field of view is feasible using the CapCalc system. Further, the use of CapCalc for data collection and subsequent analysis in terms of luminance values is fairly easy and straightforward. Comparisons between two sets of CapCalc measurements and between the photopic Pritchard and the CapCalc measurements show that the CapCalc system appears to provide satisfactory accuracy and repeatability for luminance measurements of traffic signs at night in the field. For field application the digitized pictures can be saved for further analysis and future reference. Multiple signs in a row can be captured using a single picture in order to speed up the data collection process and reduce the storage requirement. However, the luminance values of signs placed far away in multiple sign pictures may not be accurate or reliable and may include considerable variability because a relatively low number of pixels cover such a sign. To obtain the most accurate luminance values with the CapCalc system installed in a car it is recommended that the objects of interest always be placed as close to the center of the screen as possible and be as large as possible and that the engine is turned off (provide power for headlamps using another vehicle or power source) and the vehicle does not vibrate.

Although CapCalc was used successfully in this study, several improvements are necessary for the system to meet the wide range of night driving and signing conditions. These improvements include better measurement sensitivity and accuracy in the low luminance range (between 1 cd/m^2 and values close to 0 cd/m^2), a more powerful tele-objective lens (much greater than 75 mm focal length) to capture the luminance values of signs farther away more accurately (more pixels on the signs), an increase in the number of gray levels from 256 (8 bits) to a larger number such as 4,096 (12 bits), as well as some minor modifications to improve the usefulness and the statistical capabilities of the analysis software. On a more general visibility note, this study confirms that the luminance performance of retroreflective traffic signs at night depends on many factors, such as the retroreflectance of the materials used, the distance between the car and the sign, the lateral position of the sign with respect to the car, and the beam illumination. Signs placed on the left side of the roadway have considerably lower luminance values when compared with the luminance values for signs placed correspondingly on the right side of the roadway, especially when the low beams are used. It would appear that the prismatic sheeting material might be the most viable option to increase the luminance values for signs placed on the left side of the roadway under low-beam conditions. Further, if one would want to use the retroreflectance of the sheeting material instead of the luminance to match driver needs and to specify a minimum acceptable retroreflectance value, it would appear that a single minimum acceptable retroreflectance value would not be a feasible, efficient, or desirable alternative. At least two different minimum acceptable retroreflectance values for side-mounted traffic signs (not overhead signs) should be used depending on whether a retroreflective traffic sign such as a yellow warning sign is placed on the right side or on the left side of the roadway.

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Design and Operation of a Glare Evaluation Meter

H. R. BLACKWELL AND J. RENNILSON

A new physical photometer has been designed to measure the spatially weighted average equivalent luminance of all visible areas of the total visual field, relative to the average luminance of a task background subtending two degrees in diameter. The spatial weighting follows traditional practice in general. The glare evaluation meter (GEM) uses two parallel optical systems with identical components. The left system collects the average luminance of the task background at 2 degrees. The right system has a modified disability glare lens mounted in front of the objective lens. The photometer measures L and L_V and then computes the glare contrast factor (GCF). All three values are output to a backlit 3½ digit LCD meter calibrated in cd/m². The fixed-focus, hand-held GEM is battery operated. Calibration of the meter is performed by using a variable level (up to 17,000 cd/m²) source of known solid angle and rotating the meter to generate various off-axis angles. The 2-degree task background luminance can also be varied. The operation of the GEM is described and sample values of GCF are given for sample glare situations. The new meter will allow dynamic and static conditions to be measured. Sample values of GCF are given for different glare conditions and with different values of the individual disability glare factor. The readaptation correction caused by continuous exposure to the glare source will be discussed for a sample glare situation involving the headlights of an oncoming vehicle.

The concept of a visual process designated "disability glare" has a scientific background, beginning with the work of Holladay in 1927 (*1*) and Stiles in 1929 (*2*). These two researchers found independently that off-axis lighted areas of the visual field reduce on-axis visual contrast sensitivity, operating as though a veil of equivalent luminance had been placed over the central visual field commonly accepted as 2 degrees. Gradually, evidence accumulated in support of the idea that disability glare was in fact caused by the ocular stray light produced by the off-axis lighted areas, in accordance with the following general relationship:

$$L_V \sim \frac{\mathrm{E}}{\Theta^2} \qquad (1)$$

where

L_V = equivalent veiling luminance,
E = focused retinal illuminance, and
Θ = angle between an off-axis glare source and the ocular line of sight.

Calculations were made using Equation 1 covering simple patterns of luminance that provide appreciable amounts of ocular stray light. However, these calculations were generally considered insufficient to support a practical technology for dealing with disability glare under realistic conditions.

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HISTORY OF DISABILITY GLARE RELATIONSHIPS

In 1963, Fry, Pritchard, and Blackwell (*3*) produced a point-to-point mathematical approach to the calculation of ocular stray light and equivalent veiling luminance on the basis of a more explicit formula for the relationships among the parameters.

$$L_V = K \sum_{\Theta=1°}^{90°} \frac{L_s \cos\Theta}{\Theta\,(1.5 + \Theta)}\,\omega \qquad (2)$$

where

L_V = equivalent veiling luminance (cd/m²),
L_S = luminance of an individual glare element of the task surround (cd/m²),
Θ = angle between the glare element and the task (degrees),
ω = solid angle of an individual glare element (sr), and
K = disability glare factor, a proportionality parameter expressing the degree to which the eye of an individual observer produces scattered light per unit of glare element luminance.

The summation is taken between the values for Θ of 1 and 90 degrees.

Fry et al. also reported the design and use of a "disability glare lens," which represented an optical analogue of the process of stray light in reducing visual contrast sensitivity. The curvature of the aspheric lens was established by ray-tracing methods to work together with a photometer developed by Pritchard. The combination of Pritchard Photometer and Fry-Blackwell disability glare lens has worked well and made it possible to proceed with development of a practical technology for handling the disability glare aspects of lighting design and evaluation.

One major contribution to disability glare technology was CIE Report 19/2 (*4*). The state of the art in the broad area of visual performance aspects of lighting is described, as is disability glare technology as applied to the engineering of interior lighting. Thorough reading of CIE 19/2 is recommended for understanding the contribution of disability glare to the visibility level (VL) equation. The basic approach of Report 19/2 is summarized by the following equation:

$$L_V = K \sum_{\Theta=1^\circ}^{90^\circ} \frac{L_s \cos \Theta}{\Theta^2} \omega \tag{3}$$

Note that the numerators for Equations 2 and 3 are the same and include the cosine theta term. This term allows for the effect of the first cosine law of illumination in reducing L_V as Θ is increased. The denominators for Equations 2 and 3 differ. The classical equation for the disability glare effect includes Θ^2 in the denominator and is usually referred to as the Stiles-Holladay Equation because it was derived in large part from the research of Stiles and Holladay. Equation 2 should perhaps be designated the Fry-Blackwell Equation because Fry et al. were the first to suggest replacing Θ^2 with $(1.5 + \Theta)$. Report 19/2 recommends use of the Stiles-Holladay Equation (3). However, current use among U.S. lighting engineers favors the Fry-Blackwell Equation (2). Use of the Stiles-Holladay Equation is recommended unless specified otherwise.

A way out of this dilemma, described by Blackwell (*5*), is suggested because of the similarity between the denominators of Equations 2 and 3. Consider the performance curves of disability glare lenses as described by Fry et al. A linear scale of Θ is plotted on the abscissa; a log scale of relative L_V is plotted on the ordinate, covering 5 log units of potential disability glare responses. Calibration of the disability glare lens involves the determination of the best fit of the measured lens data to either Equation 2 or 3. This is usually performed by either a least squares computer fit or by a visual analog fit of the theoretical curve to the measured data. Thus, two differing calibration factors (modifiers of the disability glare factor) for Equations 2 and 3 can be derived. The best fit of the measured lens data to each equation provides quite acceptable fits over the most commonly used glare source angles.

STATIC CONDITIONS AND CIE REPORT 19/2

In 1955, Blackwell (*6*) pointed out that there are conditions in which disability glare effects will be reduced relative to values calculated from either Equation 2 or 3. These conditions require that eye and source of ocular stray light be unmoved long enough so that the visual contrast sensitivity is increased at least somewhat because of light adaptation to the luminance $(L + L_V)$, when L equals the focused luminance of the task background. Blackwell suggested that calculations of disability glare effects always include allowances for somewhat improved sensitivity when light adaptation occurs. Nonetheless, further study of this subject has lead the authors to recommend that standard usage involves no assumptions concerning light adaptation unless specified otherwise.

CIE Report 19/2 also called attention to the question of which baseline should be used in measuring values of L_V. "Sphere lighting" is recommended in the report as the baseline for use in disability glare applications involving interior illumination. In these cases, the baseline value of L_V equals 1.074 times the focused luminance. Those interested in road lighting find the sphere lighting baseline unreasonable and will probably use L_V equal to zero as their working baseline.

CIE Report 19/2 contains reference to the problem of the appropriate value to assume for the disability glare parameter (K). There appears to be remarkable good agreement that the value of this important parameter is approximately equal to 10. Fry et al. used a value of K equal to 9.2. In 1980, Blackwell and Blackwell (*7*) reported values of K obtained for 193 observers between the ages of 20 and 30 years. Through use of the glare annulus test, the average value of K was found to be 10.8. The average of 9.2 and 10.8 is equal to 10.0 the value recommended for K in Equations 2 and 3.

Report 19/2 also contains reference to systematic differences in K as a function of age and as a function of luminance level. The pupil diameter of the eye varies with luminance. The higher the luminance, the smaller the pupil and the less scattered light in the eye system. The equations presented here are collated from work by de Groot and Gebhard (*8*). The relationship between K and observer age for the lowest luminance was made available by Adrian (personal communication with Werner Adrian). Data relevant to these issues can be found elsewhere (*5*), but are presented here for the reader's convenience. The relationship of pupil size p to luminance is illustrated in Figure 1.

1. Fixed age of 20
2. Solve for $K_{20} = 8.0 + 3.523(p - 1.82)$
   where $p = \text{antilog}[.8558 - .000401(\text{Log}\,L + 8.60)^3]$ (4)

3. Solve for K_{rel}
   $A < 42.8 \quad K_{rel} = 1$ (5)
   $A > 42.8 \quad K_{rel} = \text{antilog}[1.778(\text{Log}\,A - 1.631)]$

4. $K = K_{20} \times K_{rel}$ (6)

Values of Log L are in Log cd/m²; values of A are in years of age; values of p are in mm.

DEVELOPMENT OF GLARE EVALUATION METER

The foregoing accounts of various aspects of current disability glare technology demonstrate that the technology is no longer limited to a single instrument or single instrumental mode of operating. Furthermore, continued advances in the technol-

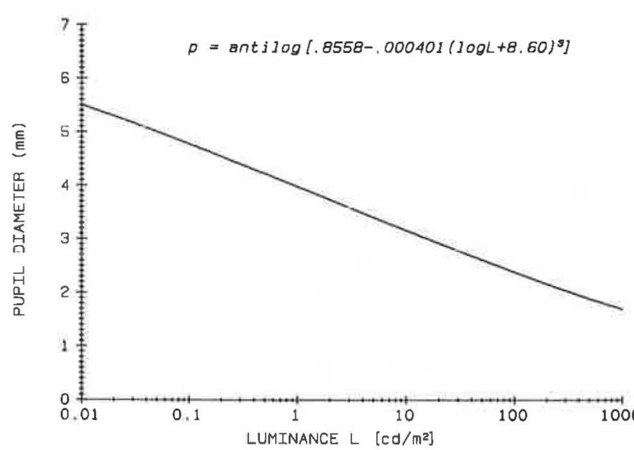

FIGURE 1 Relationship of pupil size p (mm) to adapting luminance (cd/m²).

ogy demonstrate the potential of its increased usefulness. It appears that the time has now come to offer a relatively sophisticated instrument for engineering problems in visibility and lighting.

The authors propose to designate this instrument as a glare evaluation meter (GEM). Its primary function is to measure the glare contrast factor (GCF), defined as follows:

$$\frac{L}{(L + L_V)} = \text{GCF} \tag{7}$$

where L is the luminance of the immediate background of the task detail of interest and L_V measures the spatially weighted average equivalent luminance. In CIE Report 19/2 this equation is defined as the disability glare factor/index. The authors recommend the new term as more definitive in expressing the effect of glare (i.e., reducing the luminous contrast). In addition, the authors have chosen a GCF of 0.8 as implying a reduction in contrast of 20 percent, the level below which adverse impairment occurs. Figure 2 shows a schematic of the GEM and the respective fields of view.

Dynamic conditions, such as measurement of the disability glare from the headlights of an oncoming vehicle can be recorded easily as a function of the distance between vehicles or between a pedestrian and an oncoming vehicle. The portable GEM has an analog output jack that can be used with a RAM data logger for this purpose.

The meter consists of two identical optical systems with a fixed hyperfocal distance of 14 m, which allows objects from 7 m to infinity to remain in focus. The two systems are separated by 45 mm, or slightly more than 17 mm closer than the average human interocular separation. Each system has an objective lens, baffles, field lens, photopic filter, and silicon detector. The field of view of each system is fixed at the commonly accepted foveal angle of 2 degrees used in the determination of the luminous efficiency and color-matching functions of the CIE. The systems are electronically balanced.

One system accommodates the disability glare lens, which sums the weighted field of view up to an 85-degree half angle. The glare lens has been in production since 1963 by Visioneering Laboratories, Inc., and since 1983 by Advanced Retro Technology, Inc. This lens has been reduced in size from the type normally furnished to photometers but retains the important characteristics of fit to equations 2 and 3 over four logs of veiling luminance.

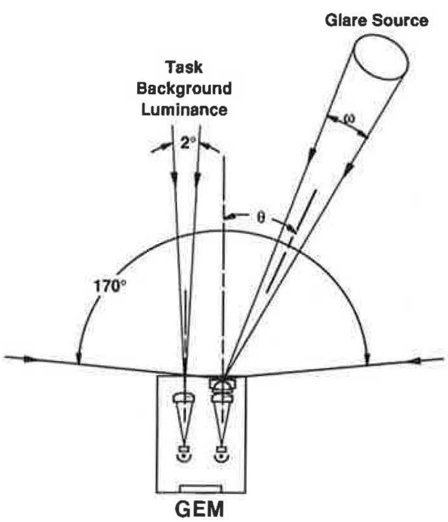

FIGURE 2 Schematic view of GEM and respective fields of view.

The meter is powered by lithium replaceable batteries to give the instrument a long life (which has not yet been determined) and measures selectively the 2-degree task background, the veiling luminance, and the glare contrast factor. Task background luminances from 0.1 to 1,999 cd/m^2 using two manual ranges are within the GEM's measurement capability.

CALIBRATION OF THE GEM

Typical Disability Glare Lens Calibration

Description of the disability glare lens is given by Fry, Pritchard, and Blackwell (*3*). Calibration of such a lens is performed in a photometric laboratory using a small intense projection source of constant luminous intensity. The lens is placed in front of a photometer, which in turn is mounted on a precision rotating table. The lens is rotated around its front surface (flat), and the photometer's response is recorded at various angles. The response data are normalized at 1 degree off the axis of the line of sight (LOS). These data are plotted as the relative veiling luminance L_V versus the angle (θ) from the LOS.

A relative theoretical relationship from either Equation 2 or 3 is computed and normalized at $\theta = 1$ degree. The lens data, also normalized at $\theta = 1$ degree, are then compared with the relative theoretical relationship. Adjustment is then made in the ordinate of the theoretical curve until it closely fits the data (least square solution). The disability glare lens is calibrated absolutely with the photometer using a single glare source of known physical characteristics at $\theta = 45$ degrees. If the "best fit" theoretical curve passes through the normalized lens data point at $\theta = 45$ degrees, then the calibration constant G_C is the value obtained by direct absolute calibration. The calibration constant G_C may be adjusted if this does not occur for the general measurement situation, or if a discrete glare source at known angles is measured, individual G_Cs may be determined. This G_C can be considered a modification of the disability glare factor to allow for instrument and lens losses that normally occur in instruments of this type. Use of the G_C thus determined, together with absolute photometric readings, will yield equivalent veiling luminances (L_V) in cd/m^2.

Glare Evaluation Meter

In the GEM, calibration is performed in a similar manner but with a least-squares fit to Equation 2 or 3. The calibration constants are then electronically introduced in the GEM to yield the correct L_V. A final check of the GEM before shipment involves linearity measurements and verification of the values of L, L_V, and GCF using a variable luminance source ($L_S = 0 - 17{,}000$ cd/m^2) with varying solid angle (ω). Checks are made at several glare source angles. Figure 3 shows the degree of fit, using a least-squares solution to the Fry-Blackwell and Stiles-Holladay equations. The calibration factors are different for these equations; the GEM may be adjusted

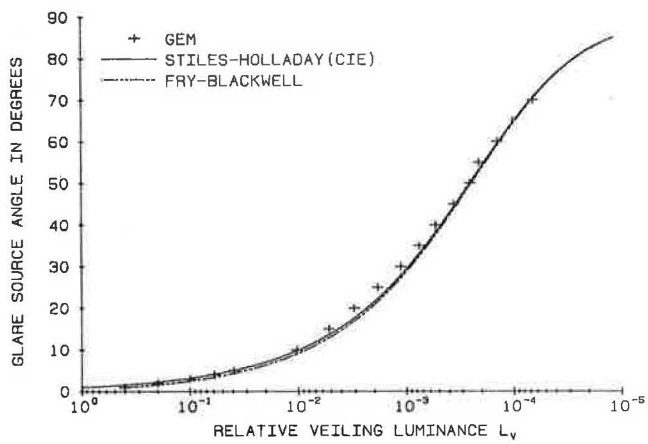

FIGURE 3 Plot of the two disability glare equations; the fit obtained to these equations by the GEM is shown by the crosses.

to yield results based on one or the other. Likewise the calibration factors may be weighted for the "best fit" to glare source angles from 1 to 20 degrees for tunnel entrances and other roadway lighting uses.

The baseline condition for the glare contrast factor differs for nighttime outdoor illumination and indoor lighting. For nighttime outdoor conditions without disability glare, L_V should equal 0. Under sphere lighting indoors, the GCF baseline condition involves setting L_V to $1.074L$.

EXAMPLES OF POSSIBLE USE OF THE GEM

The GEM was briefly field tested at different sites under static and dynamic conditions. Because the GEM is used to measure L, L_V, and GCF, various operational modes may be used. The simplest assumes that light adaptation does not occur and that the observer remains adapted to L. Under some static conditions, light adaptation does occur so that the observer is adapted to $(L + L_V)$. Calculational techniques are now available for use in tracking the observer's state of visual contrast sensitivity. A transient adaptation model assumes that the loss in visual contrast sensitivity is a result of contrast compression of an off-balance dynamic control system.

Corrections for Age and Luminance

One of the most important computations derived from the GEM data are the corrections for age and luminance. The design parameters for the GEM are based on adaptation at task background levels of 100 cd/m² and the age group 20 to 42.8 years.

Task background luminances may range from low conditions at night (0.01 cd/m² to 10 to 20 cd/m² or more). Today's design driver is older than 42.8 years (see Equation 5). One can use Equations 4–6 to compute the effect of luminance on pupil size and make corrections for luminance and age. Use of nomographs would make such computations unnecessary. Figure 4 is a nomograph that relates the K parameter to age and luminance. The resultant K parameter is then used to correct the GCF measured by the GEM (Figure 5). For example, a static nighttime task background of 5 cd/m² $(L + L_V)$ for a 60-year-old driver yields a K factor of 25. The veiling luminance effect for this driver is 2.5 times that of a 20- to 42.8-year-old driver adapted to 100 cd/m². If the GEM measured a GCF of 0.9, this driver would have an equivalent GCF of 0.8, a level at which 20 percent of his or her VL would be lost.

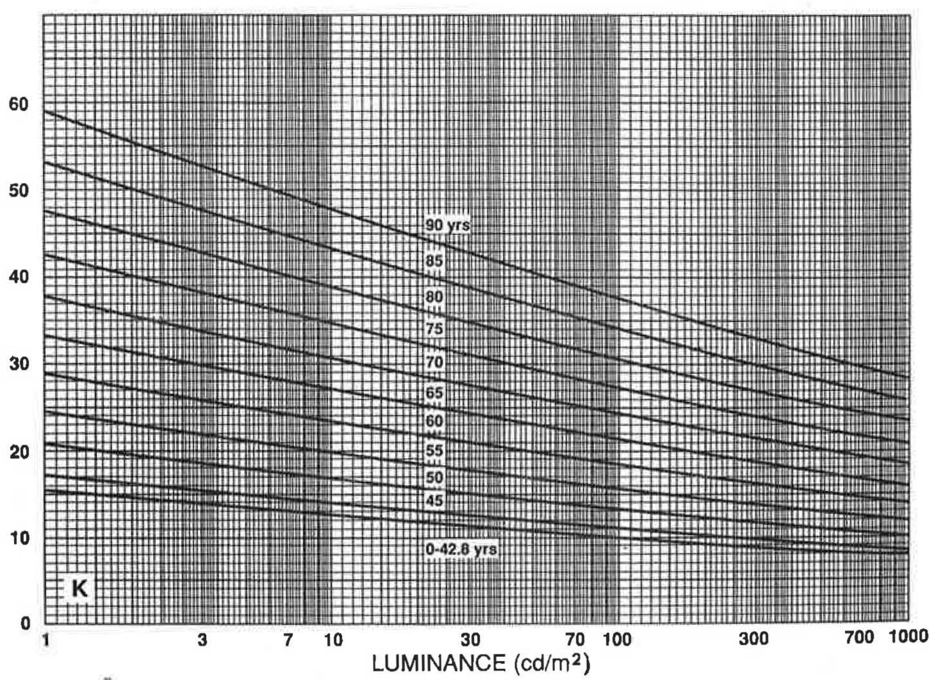

FIGURE 4 Nomograph of the disability glare factor K, adaptation luminance and age.

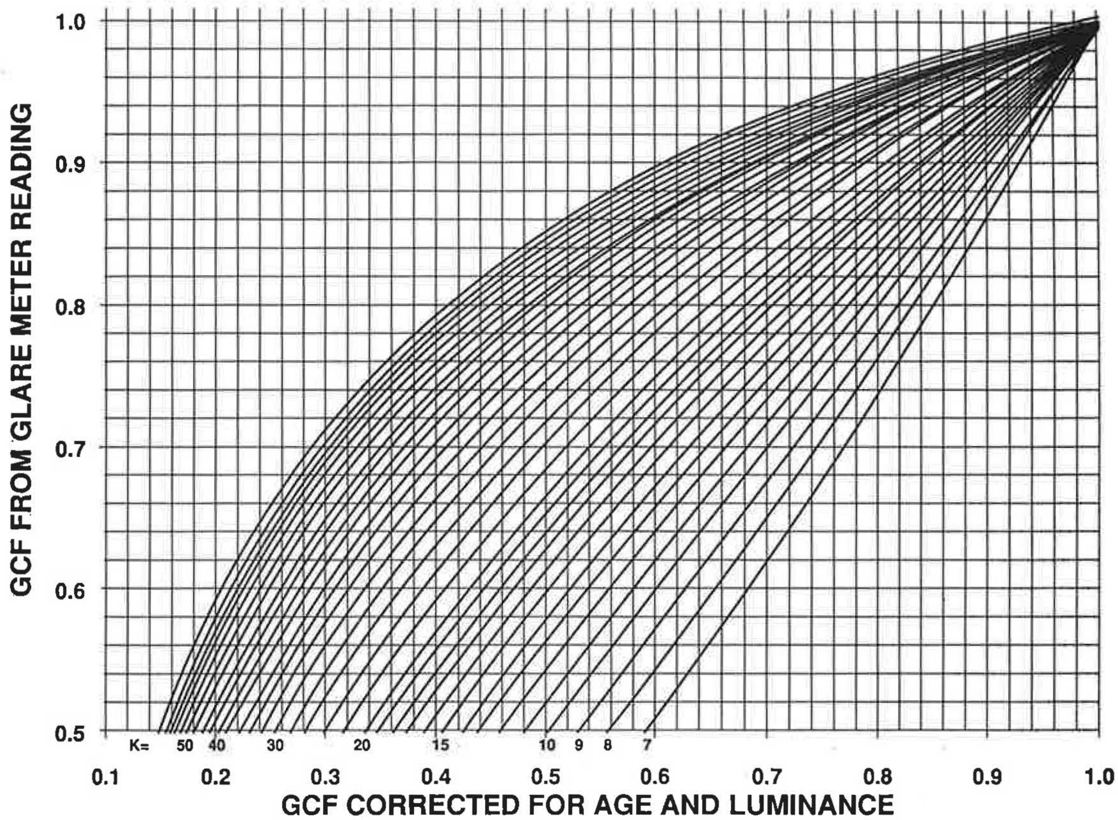

FIGURE 5 Nomograph of *K*, and GCF measured with the GEM and the corrected GCF.

Static Field Measurements

Table 1 presents measurements taken with the GEM at some typical nighttime scenes. For these static scenes the adaptation luminance is given in the $(L + L_V)$ column. The measured GCF is then corrected for the adaptation luminance and given in the column labeled "GCF corr." The asterisks denote those scenes that have more than a 20 percent loss in visibility level. The GCF, L_V values are those using the Stiles-Holladay Equation (2).

Dynamic Field Measurements

Measurements were taken with the GEM just outside a parked vehicle at the driver's eye height and at a distance of 120 ft

TABLE 1 EXAMPLES OF VARIOUS NIGHTTIME SCENES

	Description	L cd / m²	L + Lv cd / m²	GCF Meas.	GCF Corr.
1.	Parking lot with Low Pressure Sodium building lights - GM looking at entrance to suite.	0.5	.909	.55	.44*
2.	Same scene tilted downward toward sidewalk	1.3	1.55	.84	.78*
3.	Hi Pressure Sodium luminaire on 30' mask -95' from luminaire looking at pavement under source.	2.3	2.35	.98	.97
4.	Same scene 25' from luminaire.	2.3	2.53	.91	.88
5.	Store front with bare fluorescent lamps (diffuse sign missing) GM looking at store entrance.	0.9	1.73	.52	.44*
6.	Shopping center parking lot 120' from parked cars and one luminaire - 3 Hi Pressure Mercury lamp luminaires in vicinity.	2.6	3.61	.72	.65*
7.	80' away	2.6	3.21	.81	.75*
8.	25' away	2.9	3.29	.88	.84
9.	Another Hg luminaire 35' away looking at parking area.	3.1	3.60	.86	.81
10.	Same area, looking at entrance to store.	0.9	1.41	.64	.56*

* Scenes having over 20% loss in visibility level.

in front of the vehicle at the right edge of the pavement. The low beam of the vehicle was turned on, and measurements of the GCF were obtained from an oncoming vehicle (Nissan Maxima) whose headlight distribution pattern was unknown. Figure 6 shows the GCF as a function of approaching distance for the high-beam case on a two-lane road. The visual angle between the GEM and the vehicle was between 2 and 8 degrees. This road was straight with a slight downgrade. The oncoming vehicle turned a corner into the right lane at about 530 ft. Figure 7 is similar to Figure 6, but in this case the oncoming vehicle was stopped at 730 ft and its headlights were turned on before it proceeded toward the GEM. In each figure the level at which a 20 percent loss in visibility level occurs is indicated, first for 20- to 42.8-year-old drivers and then for 65-year-old drivers. Vertical lines show the intersection distances at points at which the 20 percent impairment begins. In Figures 6 and 7 these threshold levels indicate that the 20 percent loss for a 65-year-old could result in a greater distance over which objects on the roadway of low contrast might not be seen as compared the distance for with younger drivers.

SUMMARY

The convenience of obtaining the photometric and glare measurements with one meter will provide greater ease in measuring conditions in which disability glare has an adverse effect. Although the examples given are preliminary in nature,

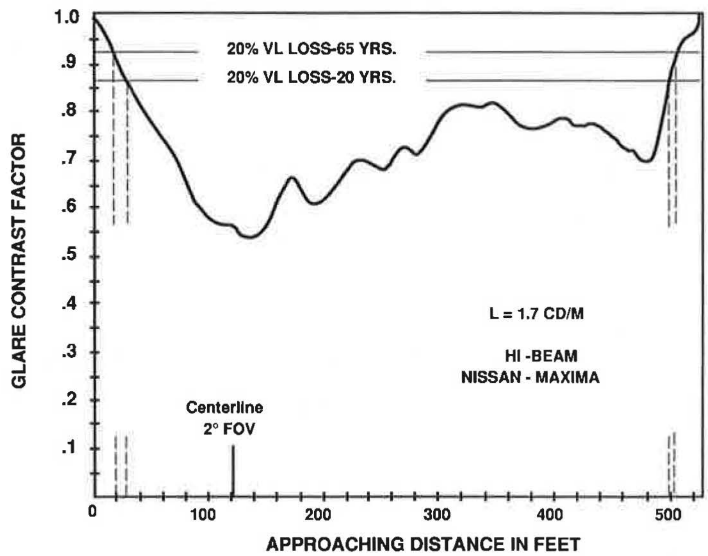

FIGURE 6 Dynamic measurement of oncoming vehicle headlight glare for high beams; vertical lines show the distance at which the transition occurs.

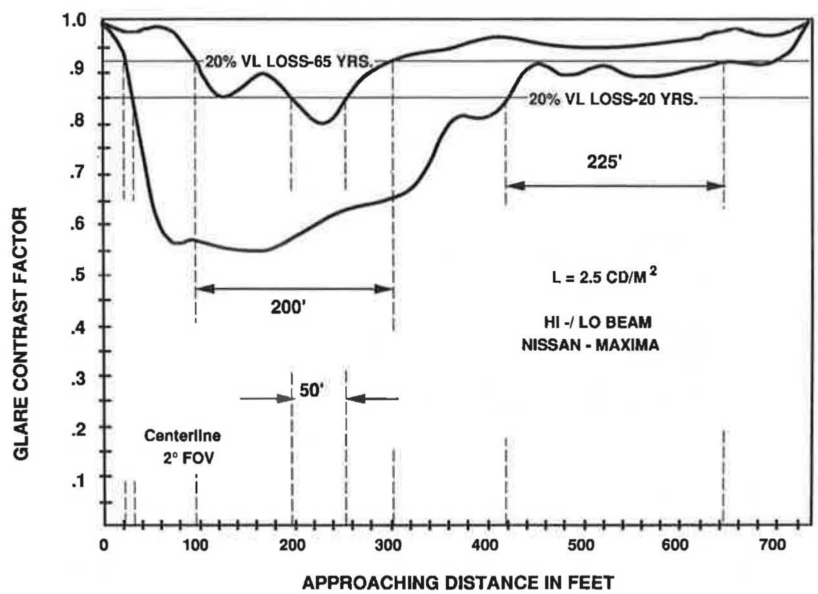

FIGURE 7 Dynamic measurement of oncoming vehicle headlight glare for low and high beams at a longer distance over an undulating roadway.

the method holds promise for quantifying disability glare in dynamic conditions.

ACKNOWLEDGMENT

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Tunnel Lighting: Comparison and Tests of Symmetrical, Counter-Beam, and Pro-Beam Systems

J. M. DIJON AND P. WINKIN

Three tunnel lighting systems—symmetrical, counter-beam (CBL), and pro-beam (PBL)—were compared under the same geometrical and weather conditions to determine their advantages and disadvantages in terms of visibility. The PBL system was found to have no advantages over the other two systems, and it should be used in combination with light, diffusing tunnel walls and road surfaces. The symmetrical system was found to provide good guidance when used with luminaires mounted in a continuous line, and the CBL system was found to ensure good perception of contrast and an acceptable level of glare, provided that certain conditions are met.

The main problem of tunnel lighting concerns the entrance zone extended over the length inside the tunnel corresponding to the safe stopping sight distance (SSSD).

The level of luminance L_{th} required in the threshold zone is defined in relation to the luminance level in the tunnel access zone L_{20} at a distance equal to the SSSD from the tunnel mouth, according to the ratio $k = L_{th}/L_{20}$, where L_{th} is the luminance in the threshold zone and L_{20} is the luminance within a field of 20 degrees measured in the access zone in the direction of the traffic, where the center of the field of measurement coincides with the center of the tunnel.

However, on examination of the different recommendations it can be seen that the ratio sometimes shows wide deviations between standards, and even within the same recommendation [e.g., depending on whether the lighting system used is symmetrical or asymmetrical with counter-beam lighting (CBL)].

For example, the values of k recommended in Commission Internationale de l'Eclairage (CIE) (International Commission on Illumination) No. 88 (*1*) are lower for CBL than for a system with symmetrical distribution.

How can there be such discrepancies between different standards? There are a number of explanations. If the tunnel is in use, the difficulties and dangers imposed by the traffic may make conducting experiments nearly impossible. Often the tests are carried out before the tunnel is opened, but this is even more irrelevant, and the time available is usually short. Many experiments are carried out at night in order to avoid traffic, but the conditions then are totally different from those during the day, and even when experiments are carried out during the day, it is difficult to get the same field of experimentation over a period long enough to be representative of different weather conditions. Thus, to take the different conditions into account it is necessary to extrapolate from the results of laboratory experiments.

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For example, the contrast quality factor of ≥ 0.6 for CBL cited in CIE 88, namely the ratio L_r/E_v, where L_r is the luminance of the road and E_v is the illuminance of the obstacle, can only be fully verified in the tunnel at night.

During the day, however, this factor is significantly less than 0.6, and may even be of the order of 0.4 in the first 40 m of the tunnel. This, in the opinion of the author, is mainly because the principle is based on theoretical notions that are insufficiently founded on daylight conditions in the tunnel entrance. The values put forward for the contrast quality factor are generally based on measurements carried out at night.

EXPERIMENTAL SITUATION

The experimental situation consists of a motorway tunnel that in 1975 was equipped with a symmetrical system of continuous strip lighting down the center of the ceiling. A second, asymmetrical, system—basically a CBL system—was installed in the threshold zone. The two types of lighting can be used alternatively. In 1990, the CBL system was converted to an asymmetrical system with the flux directed toward oncoming traffic by turning the luminaires through 180 degrees in azimuth.

The aim of the tests was to compare these three lighting systems in the tunnel under the same geometrical and weather conditions, and thus to deduce their advantages and disadvantages in terms of visibility, particularly to determine whether the three systems justified different choices for the ratio $k = L_{th}/L_{20}$.

EXPERIMENTAL SET-UP

Common Elements of Symmetrical and Asymmetrical Systems

The geometry of the experiments was as follows:

- Motorway tunnel, 2 unidirectional bores.
- Three traffic lanes, 3.75 m each.
- Total width: 14.25 m.
- Ceiling height: 5.50 m.
- Length of tunnel: 467 m.
- Speed of traffic: 120 kph.

The orientation was south to north for the bore under trial. The experiments were conducted under an open environment giving a luminance L_{20} of 4500 cd/m^2 (Figure 1).

The tunnel road surface was transversely corrugated concrete, light and highly diffusing, with $S1 = 0.16$ and $q_o = 0.10$. The tunnel wall surface was specular ceramic for the first 50 m of the tunnel entrance, with a coefficient of reflection of $\rho = 0.7$. The wall surface for the rest of the tunnel was light-colored concrete with a coefficient of reflection of $\rho = 0.5$.

Symmetrical Lighting System

The symmetrical lighting system was installed in 1977. The lighting units were mounted in two continuous lines on the ceiling: LPS 131 W for sunny conditions and fluorescent lamps for dark and night levels.

Asymmetrical Lighting Systems

In addition to the symmetrical system, four lines of luminaires with asymmetrical light distribution were installed on the outside of the existing lines. For the first 2 years these luminaires were oriented toward oncoming traffic (counter-beam lighting). In 1990, the units were rotated 180 degrees in azimuth to shine in the direction of traffic flow. This system is called pro-beam lighting (PBL). The lighting fittings were equipped with HPS 400 W sources. Figure 2 shows the levels measured at night for the three systems with the arrangement of the luminaires in the threshold zone. Figure 3 shows the polar diagrams I_{cd} for the three systems.

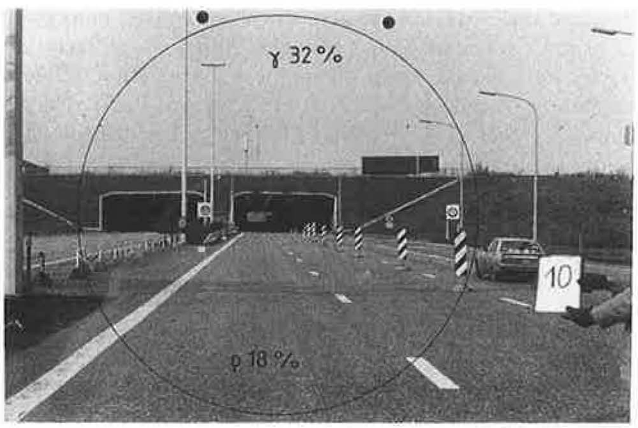


FIGURE 1 Wevelgem tunnel, 160 m from portal.

THEORETICAL CONDITIONS OF VISIBILITY OF OBSTACLES

If L_b is the luminance of the background, generally taken to be the luminance L_r of the road, and L_o is the luminance of the obstacle, the intrinsic luminance contrast (C_{int}) is then defined as follows:

$$C_{\text{int}} = (L_o - L_r)/L_r \tag{1}$$

This intrinsic contrast is defined at a short distance from the obstacle, without taking into account the various interference luminances, such as the veiling luminance (L_v), the atmospheric luminance (L_{atm}) or the windscreen luminance (L_{wscr}).

Depending on whether condition L_o is greater or less than L_r, the intrinsic contrast will be positive (from 0 to $+\infty$) or negative (from -1 to 0).

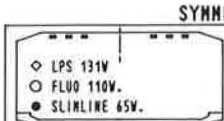
When the absolute value of the intrinsic contrast is less than a certain value, conditions are below the threshold of visibility. That is, they are below the threshold contrast C_{th}, which in the particular case of tunnels is taken to be

$$|C_{\text{th}}| = 0.2 \tag{2}$$

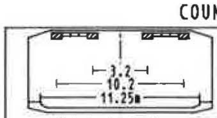
If the simplifying assumption is made that obstacles are perfect diffusers, Equation 1 becomes

$$C_{\text{int}} = \frac{\rho \times E_v}{\pi \times L_r} - 1 \tag{3}$$

SYMMETRICAL LIGHTING SYSTEM

 ◇ LPS 131W ○ FLUO 110W. ● SLIMLINE 65W.	Horizontal illuminance road E_h (lux)	Luminance road L_r (cd/m²)	Vertical Illuminance road for H=0.3m E_v (lux)	Walls luminance L_w (cd/m²)	L_r / E_v
VERY SUNNY	5700	400	2400	510	0.15

COUNTER BEAM LIGHTING SYSTEM (C.B.L.)

 C.B.L. luminaires; Symmetrical luminaires	Horizontal illuminance road E_h (lux)	Luminance road L_r (cd/m²)	Vertical illuminance road for H=0.3m E_v (lux)	Walls luminance L_w (cd/m²)	L_r / E_v
VERY SUNNY	4900	400	590	510	0.68

PRO BEAM LIGHTING SYSTEM (P.B.L.)

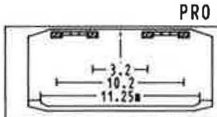
 P.B.L. luminaires; Symmetrical luminaires	Horizontal illuminance road E_h (lux)	Luminance road L_r (cd/m²)	Vertical Illuminance road for H=0.3m E_v (lux)	Walls luminance L_w (cd/m²)	L_r / E_v
VERY SUNNY	3900	380	3400	395	0.11

FIGURE 2 Lighting levels measured at night for three systems.

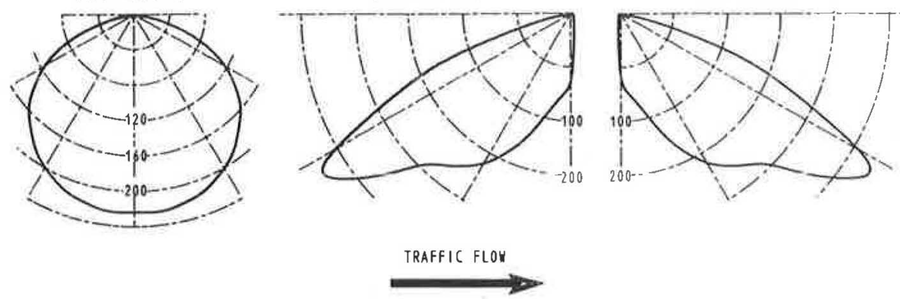


FIGURE 3 Polar diagrams I_{cd} for three systems.

where E_v is the vertical illuminance of the obstacle and is the coefficient of reflection of the obstacle.

The obstacle will be invisible when

$$-C_{th} < C_{int} < +C_{th} \quad (4)$$

From equations 3 and 4 it can be deduced that obstacles with coefficients of reflection ρ between the two following limits will be invisible.

$$\frac{\pi \times L_r}{E_v}(1 - C_{th}) < \rho < \frac{\pi \times L_r}{E_v}(1 + C_{th}) \quad (5)$$

For the three photometric distributions considered—symmetrical, CBL, and PBL—the L_r/E_v ratios were as follows for the Wevelgem tunnel (see Figure 2).

Symmetrical distribution: $L_r/E_v = 0.15$ (6.1)

CBL distribution: $L_r/E_v \geq 0.68$ (6.2)

PBL distribution: $L_r/E_v = 0.11$ (6.3)

Symmetrical Lighting System

From equations 2, 5, and 6a, it can be deduced that obstacles with a coefficient of reflection (ρ) between 0.38 and 0.56 will have an intrinsic contrast (C_{int}) less than the threshold contrast (C_{th}). A light, diffusing surface that enables the ratio E_H/L_r to be made lower, thus lowering the lighting power required, would appear to be most suitable for a symmetrical system.

CBL System

From equations 3 and 6b it can be deduced that whatever the coefficient of reflection (ρ) of the obstacle is, the intrinsic contrast (C_{int}) will always be negative and greater than the threshold contrast (C_{th}). The lighter and more reflecting the surface (high $S1$), the more negative will be the contrast, giving the family of curves $R4$ with $q_o > 0.1$.

PBL System

From equations 2, 5, and 6c, it can be deduced that obstacles with a coefficient of reflection (ρ) between 0.25 and 0.38 will have intrinsic contrast (C_{int}) less than the threshold contrast (C_{th}). A light, diffusing surface that enables the ratio E_H/L_r to be made lower, thus lowering the lighting power required, would appear to be the most suitable for a PBL system.

VISIBILITY OF OBSTACLES AT NIGHT

Practical verification of the first conclusions on the perception of contrast was carried out at night. Three 20- x 20-cm obstacles were placed across the highway, each with a different coefficient of reflection (ρ = 0.16, 0.36, and 0.75). The luminance values of the roadway (L_r) and of the obstacle (L_o) were measured for each obstacle.

Experiment I: Symmetrical Lighting System

For this experiment, L_r = 400 cd/m^2 at night. For Obstacle 1, ρ = 0.75, L_o = 580 cd/m^2, and C = +0.45. For Obstacle 2, ρ = 0.36, L_o = 380 cd/m^2, and C = −0.05. For Obstacle 3, ρ = 0.16, L_o = 270 cd/m^2, and C = −0.32. The tests confirmed that Obstacle 2, with a coefficient of reflection ρ = 0.36, is invisible (see Figure 4).

Experiment II: CBL System

For this experiment, L_r = 400 cd/m^2 at night. For Obstacle 3, ρ = 0.16, L_o = 90 cd/m^2, and C = −0.77. For Obstacle 2, ρ = 0.36, L_o = 170 cd/m^2, and C = −0.57. For Obstacle

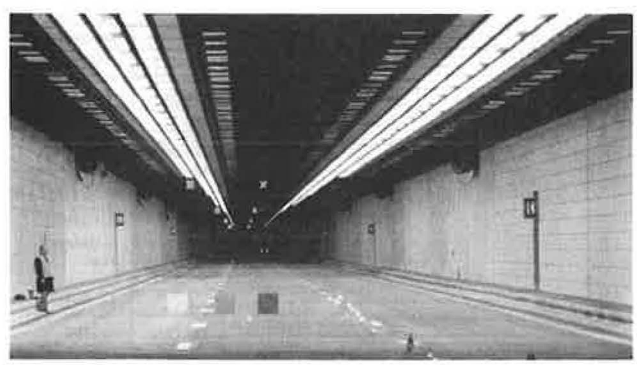


FIGURE 4 Targets at night under symmetrical lighting system.

1, $\rho = 0.75$, $L_o = 260$ cd/m², and $C = -0.35$. The tests confirmed that the three obstacles are visible with negative contrast (see Figure 5).

Experiment III: PBL System

For this experiment, $L_r = 380$ cd/m² at night. For Obstacle 1, $\rho = 0.75$, $L_o = 618$ cd/m², and $C = +0.63$. For Obstacle 2, $\rho = 0.36$, $L_o = 400$ cd/m², and $C = +0.05$. For Obstacle 3, $\rho = 0.16$, $L_o = 228$ cd/m², and $C = -0.4$. The tests confirmed that Obstacle 2, with a coefficient of reflection of $\rho = 0.36$, is invisible (see Figure 6).

VISIBILITY OF OBSTACLES BY DAY

The test conditions were chosen to correspond with the actual situation of a driver who is approaching the mouth of a tunnel and must react to the perception of an obstacle on the road at a distance corresponding to SSSD.

For each of the lighting systems, three series of measurements and observations were conducted, at distances of (a) 60 m from the obstacles, (b) 160 m from the obstacles, and (c) 160 m from the tunnel portal.

The 3 targets were moved successively from the portal of the tunnel to 70 m inside the tunnel in the threshold zone.

The series of measurements (L_r, L_o, E_v, L_{20}, and L_{atm}) were carried out mostly during good weather conditions (sunny and very sunny) with horizontal illuminance levels in the tunnel access zone on the order of 100,000 lux and luminances L_{20}=4,500 cd/m² and L_{seq} = 230 cd/m².

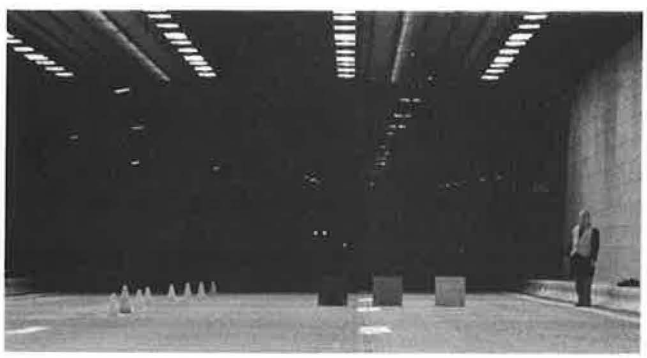


FIGURE 5 Targets at night under CBL system.

FIGURE 6 Targets at night under PBL system.

Atmospheric Luminance

Padmos (*2*) has shown that in Holland during at least 85 percent of the day $L_{atm} = 0.00152\ d\ L_{20}$, where d is the distance measured from the mouth of the tunnel in the access zone. This gives the following value of contrast:

$$C = \frac{(L_o + L_{atm}) - (L_r + L_{atm})}{L_r + L_{atm}} \qquad (7)$$

From equations 1 and 7 it can be deduced that

$$C = C_{int} = \frac{L_r}{L_r + L_{atm}} \qquad (8)$$

The atmospheric luminance reduces the intrinsic contrast, without changing the sign.

Applying Padmos' formula for a distance of 160 m from the tunnel mouth and for luminances L_{20} = 4,500 cd/m² measured at the site of the tunnel, L_{atm} = 1,000 cd/m².

At 160 m from the tunnel mouth, values of L_{atm} = 260cd/m² were measured. For L_r values of 400 cd/m² in the threshold zone, the contrast C is reduced to 60 percent of the intrinsic contrast C_{int}.

Contribution of Daylight in Tunnel Entrance Zone

This factor has a significant effect in displacing the values of the ratio L_r/E_v downward. At 2 p.m., with external illuminance of 95,000 lux and L_{20} = 5000 cd/m², the vertical illuminance was 50,000 lux at the tunnel mouth, 1,900 lux at 20 m inside the tunnel, 540 lux at 50 m, and 190 lux at 70 m. The following is derived from equations 3 and 8:

$$C = \left(\frac{\rho \times E_v}{\pi \times L_r} - 1\right) \frac{L_r}{L_r + L_{atm}} \qquad (9)$$

An obstacle that has a negative intrinsic contrast at night can take on a positive contrast or have a contrast below the threshold contrast.

Effect of Wall Lighting on Visibility in Threshold Zone

The Wevelgem tunnel walls are tiled for the first 50 m with light, specular ceramic with a coefficient of reflection of ρ = 0.7, and the walls of the interior of the tunnel are covered in light, diffusing cement with a coefficient of reflection of ρ = 0.5.

With CBL in particular, for which the vertical illuminance of obstacles should be as low as possible, one-third of the vertical lighting comes from the luminaires and two-thirds from the clear walls and the clear, diffusing roadway.

Results of Measurements

For the sake of clarity, the intermediate results for one series (a) of measurements only, at a distance of 60 m from the obstacles, are given here. The differences in the results of the series are due entirely to L_{atm} increasing from series (a) to (c).

Figures 7a, 7b, and 7c show the following, for the symmetrical (7a), CBL (7b), and PBL (7c) systems, respectively.

For the three systems, L_r is greater than 1,000 cd/m² at the tunnel portal and is always greater than 400 cd/m² at 70 m (at night L_r 400 cd/m² in all three systems).

For the symmetrical system, the ratio L_r/E_v remains relatively constant at between 0.1 and 0.2 (at night L_r/E_v = 0.2); for CBL, L_r/E_v varies between 0.1 and 0.45, without reaching the ratio of 0.6 attained at night; for PBL, L_r/E_v remains relatively constant at between 0.05 and 0.1 (at night L_r/E_v = 0.1).

For the symmetrical system, the contrast (C) is positive up to approximately 5 m and remains positive for the obstacle

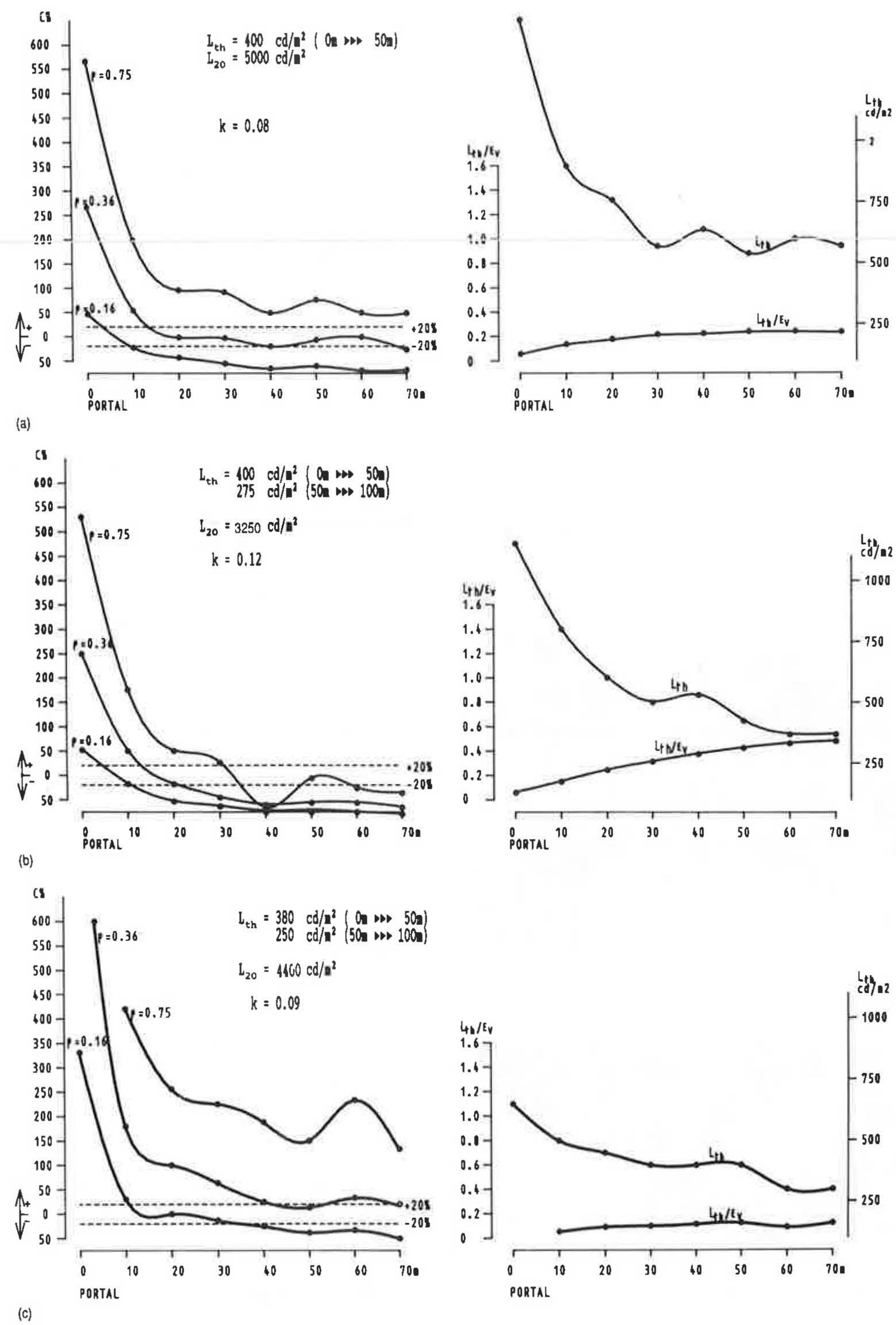


FIGURE 7 Results of measurement of visibility of obstacles by day for three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL.

with a coefficient of reflection of $\rho = 0.75$. The obstacle with a coefficient of reflection of $\rho = 0.36$ will become invisible at 15 m and remain invisible up to 70m. The obstacle with a coefficient of reflection of $\rho = 0.16$ will remain invisible from 5 to 10 m and will become visible once more but with negative contrast beyond 15m.

For CBL, the obstacle with a coefficient of reflection of $\rho = 0.75$ will have a contrast (C) that is positive from 0 to 30 m. It will be invisible between 30 and 40 m and will have negative contrast beyond 40 m.

The contrast of the obstacle with a coefficient of reflection of $\rho = 0.36$ will change from positive to below the threshold contrast beyond 12 m; it will become visible once more with negative contrast at 22 m.

The obstacle with a coefficient of reflection of $\rho = 0.16$ will become invisible at 5 m and will become visible again, but with negative contrast, at 10 m.

For PBL, the values of contrast for the three targets from the tunnel mouth up to 70 m are similar to those obtained with the symmetrical system.

The obstacle with a coefficient of reflection of $\rho = 0.36$ is almost always invisible or at the limit of the threshold contrast (C_{th}).

Figures 8a, 8b, and 8c show the variation in contrast for the three systems. Note however that the photographs were taken from a shorter distance (5 m).

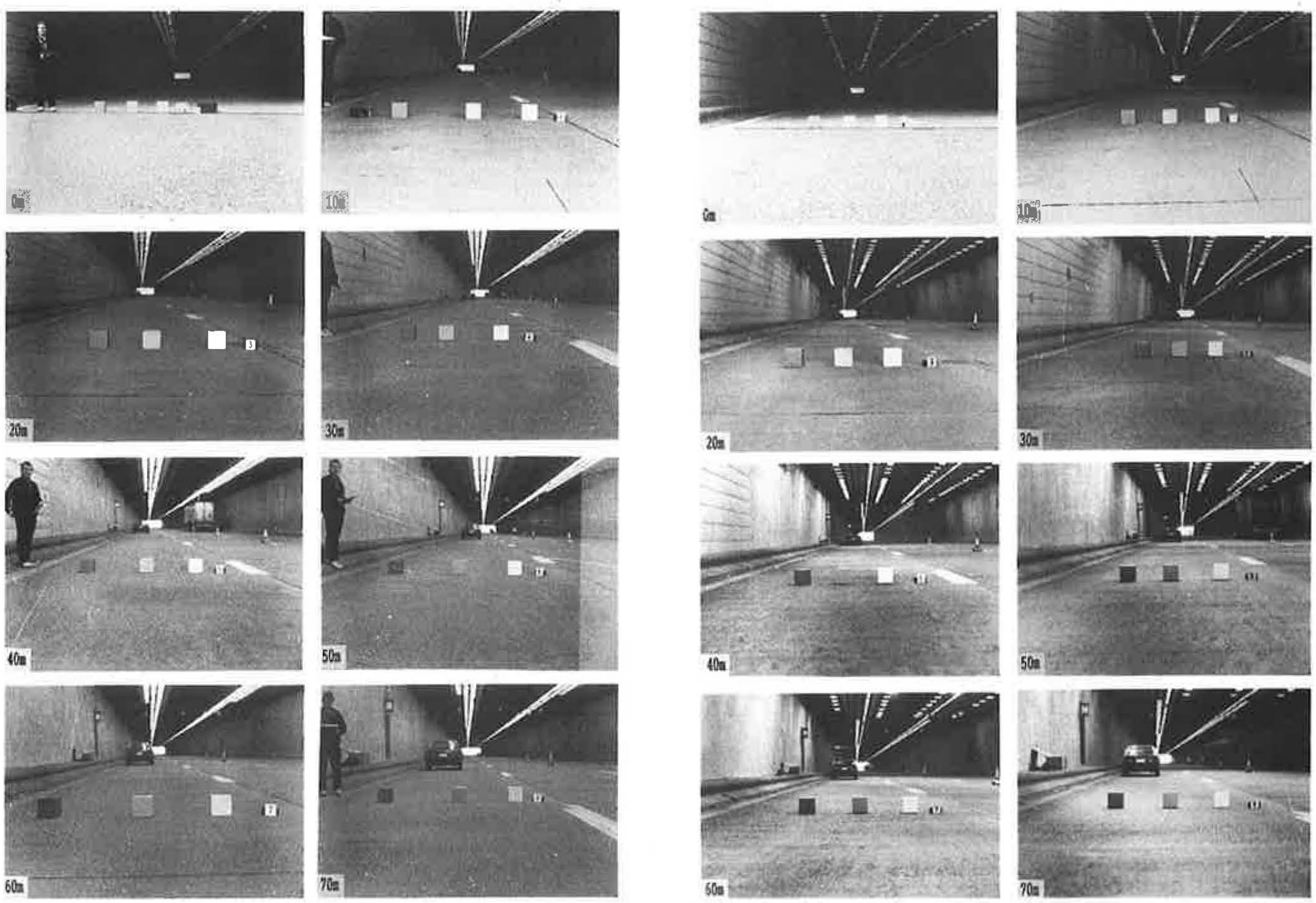
From these contrast measurements from the three targets, one can interpolate the contrast values for obstacles with coefficients of reflection between 0.75 and 0.16 and trace the invisibility zones $|C| \leq 2$ for obstacles with $0.16 < \rho < 0.75$ from the tunnel portal up to 70 m.

Figures 9a, 9b, and 9c show the invisibility zones for the three systems with the contrast measured at 60 m from the obstacle, from the tunnel portal up to 70 m inside the tunnel. For the symmetrical system (Figure 9a), the obstacle with a coefficient of reflection ρ between 0.3 and 0.5 is critical and will never be seen. For CBL (Figure 9b), for the same obstacle, whatever its coefficient of reflection (ρ), there will be a position at which it will be invisible or its contrast will be reversed. The light obstacle with $\rho > 0.7$ (statistically infrequent) will not be seen. For PBL (Figure 9c), the dark obstacle with coefficient of reflection ρ between 0.15 and 0.35 (statistically significant) is critical and will never be seen.

Figures 9–11 illustrate the effect of the viewing distance. Because the atmospheric luminance L_{atm} increases with distance, the invisibility zones also become greater with distance. This confirms the previous conclusion that the atmospheric luminance reduces the contrast.

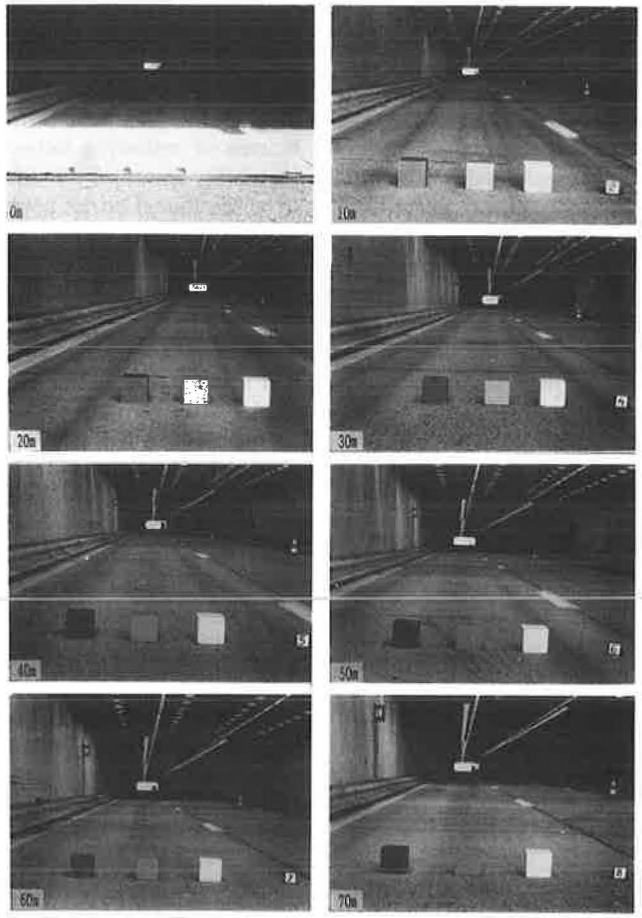
CONCLUSIONS

- L_{atm} is critical for all three systems. The only remedy is to lower the speed limit in order to reduce SSSD.



(a) (b)

FIGURE 8 Three obstacles located up to 70 m from tunnel portal under three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL. **(*continued on next page*)**



(c)

FIGURE 8 *(continued)*

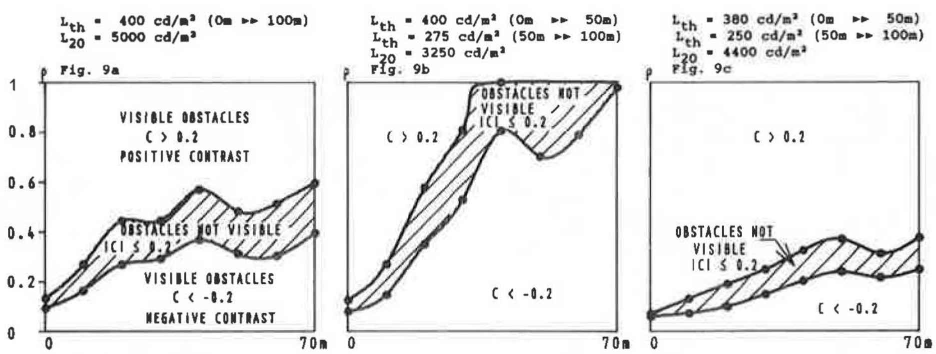


FIGURE 9 Zones of visibility 60 m in front of obstacles for three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL.

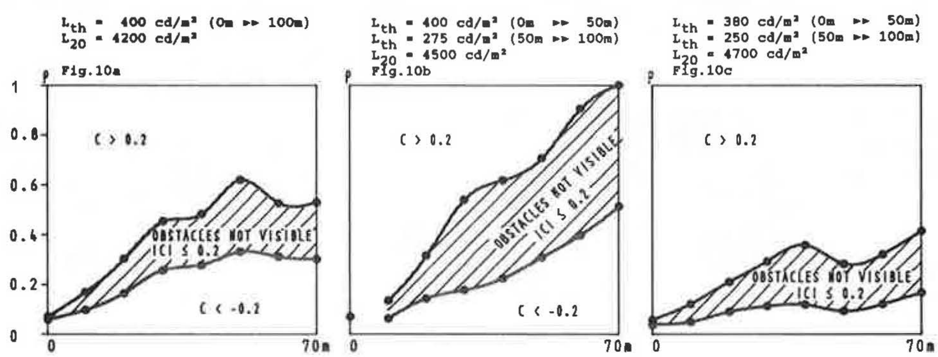


FIGURE 10 Zones of visibility 160 m in front of obstacles for three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL.

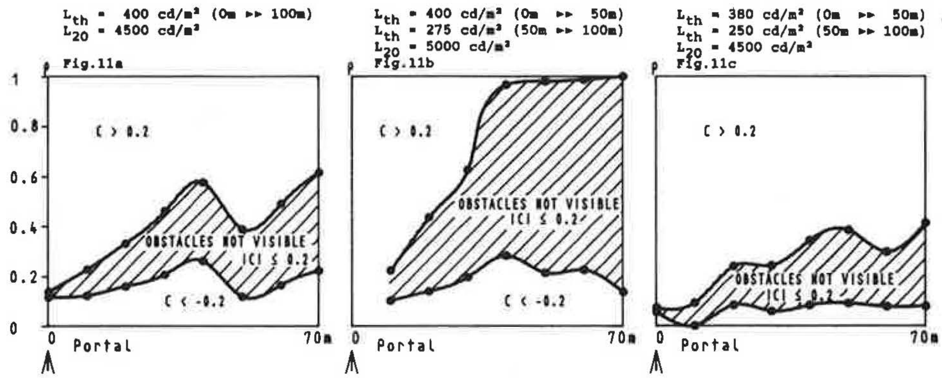


FIGURE 11 Zones of visibility 160 m in front of tunnel portal for three lighting systems: (a) symmetrical, (b) CBL, and (c) PBL.

- There are, for all three systems, invisibility zones of similar importance. Accordingly, there is no justification for reducing the ratio $k = L_{th}/L_{20}$ for any of them.
- Preference for the PBL system is not justified because the system does not have any advantages over the symmetrical or CBL systems. Moreover, it demands higher installed lighting power. Dark obstacles (statistically frequent) have poor visibility as dark vehicles, especially because of the light distribution of the luminaires there is no perceptible flickering on the back windscreens.
- The PBL system should be used in combination with light, diffusing tunnel walls and road surfaces.
- The symmetrical system provides good guidance when it is used with luminaires mounted in a continuous line. A flickering effect on the rear windscreens is not distracting and ensures perception of moving vehicles. This system should be used in combination with light tunnel walls and a light, diffusing road surface.
- The CBL system ensures good perception of contrast, a reduction in installed power, and an acceptable level of glare, provided that certain conditions are met:
  - The part of the walls with high luminance must be limited to a level of 1 m in order to reduce the E_v of the obstacles.
  - The light intensity emitted by the luminaires in the direction of the traffic must be limited.
  - A light, specular road surface must be used to enhance installed lighting power.
  - The photometric distribution must be such that the vertical angle of the beam is as high as possible but not higher that 56 degrees, and the intensities between 70 and 90 degrees should be kept as low as possible to avoid glare.

REFERENCES

1. *CIE Publication No. 88: Guide for the Lighting of Road Tunnels and Underpasses.* International Committee on Illumination, Paris, France, 1990.
2. P. Padmos. Glare and Tunnel Entrance Lighting. *CIE Journal,* Vol. 3, No. 1, 1984.

Seven Years of Illumination at Railroad-Highway Crossings

RICHARD A. MATHER

The results of 34 crossings that were installed during the first 7 years of illumination of railroad-highway grade crossings in Oregon are discussed here. The specifications, along with the orientation of the lights to the road and railroad track, are discussed. The dates of installation for each crossing, number of tracks, orientation of the lights at the crossing, and results of the various light readings are presented. Installation costs are discussed, and the method used to attain the goal of $2,000 per installation is described. Some of the problems encountered and the accident history during the 7 years are analyzed. It is concluded that illumination has provided an effective low-cost alternative for improving crossing safety at night.

In the early 1980s, officials of the Oregon Public Utility Commission (OPUC), recognizing that the majority of grade crossings do not qualify for installation of expensive automatic warning signals, began searching for low-cost alternatives for safety improvements. At that time, the agency began studying illumination for crossings that had regular nighttime (4 p.m. to 7 a.m.) train movements and were too low on the statewide crossing priority list (low train or vehicle traffic volumes) to qualify for automatic warning devices.

OPUC staff was aware that research on the use of conventional street light luminaires in the vicinity of grade crossings was being done at Kansas State University and in the city of Lincoln, Nebraska. OPUC, interested railroads, and public road authorities conducted three demonstration projects in Oregon: at the 5th and 6th Street crossings in Ontario and at 170th Avenue in Washington County. Results from the projects were presented at a formal hearing conducted by OPUC in 1977. After the hearing, OPUC formed a crossing illumination advisory committee and initiated additional research at crossings in three different settings: metropolitan area, small city, and rural area.

After a second formal hearing on crossing illumination, OPUC staff was directed to take the following actions.

1. Establish a list of eligible grade crossings. (The two criteria for eligibility were mentioned previously.)
2. Circulate the list for review and comment to appropriate public road authorities and railroads, the State Highway Division, and the County Engineers' Technical Advisory Committee.
3. Invite applications for illumination.
4. On receipt of an application for illumination, the following steps were taken:
   a. Serve it on all interested parties, including any advisory group established by the County Engineers' Technical Advisory Committee.
   b. Request that the highway division provide accident data for a distance of 200 ft on each side of the crossing.
   c. Conduct an on-site meeting at the crossing.
   d. Draft and circulate to all parties a memorandum summarizing the action requested in the application along with any data and arrangement of luminaire developed at the on-site meeting.
   e. Institute a formal investigation along with circulation of a staff-proposed final order.
   f. Issue a final order after expiration of the comment period (assuming all parties agree on what should be done).

Funding for installation of the illumination devices was provided by the following sources: State Grade Crossing Protection Account (GCPA), 90 percent; railroad, 5 percent; and road authority, 5 percent. The cost of electrical power for illumination devices is normally shared equally by the railroad and road authority.

INSTALLATION SPECIFICATIONS

1. At least one luminaire shall be mounted on each side of the track at the crossing. Luminaires should be located so that protective devices at the crossing will be directly illuminated.
2. Luminaires shall be oriented toward the railroad track to provide at least 1 ft-c of illumination on the vertical plane 5 ft from the centerline of the track. Maximum permissible level of illumination and exact orientation of the luminaire will be determined case by case. Factors at the site, including the ambient level of nighttime illumination, need to be considered. The maximum level of illumination is related to the level of lighting on the roadway approaches. The level of illumination should be sufficient to alert drivers to the crossing ahead and to any railroad equipment occupying the crossing, but should not be so bright as to create a blinding effect for motorists in the area immediately beyond the crossing. Cutoffs will normally be used on luminaires to minimize this blinding effect.
3. Luminaires should illuminate an area along the track that is 50 percent wider than the traveled width of the road. The illumination should cover a distance equal to the normal height of rail equipment (at least 15 ft above the top of the rail).
4. Poles holding luminaires should be located so that they can be maintained from the highway right-of-way.

Figure 1 shows an example of an installation.

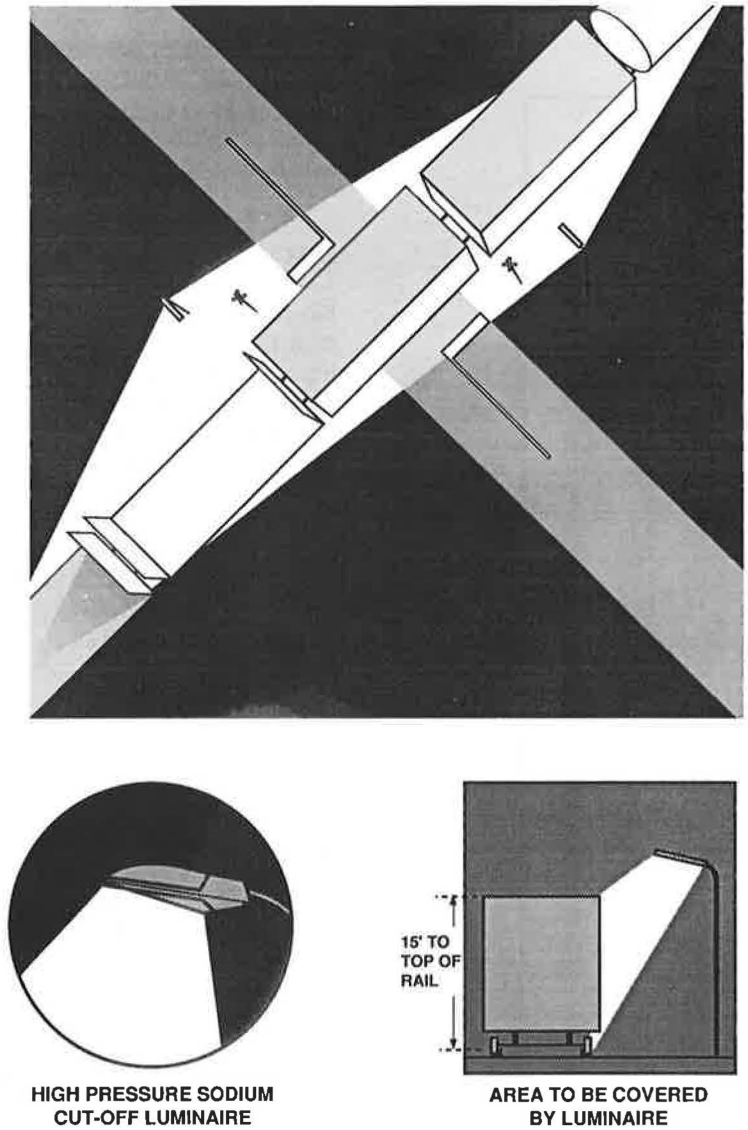


FIGURE 1 Example of installation of luminaires.

NUMBER OF CROSSINGS ILLUMINATED

Before undertaking the crossing illumination investigation, OPUC staff members ordered some type of crossing illumination at nine grade crossings in Oregon. At 18 crossings, local road authorities paid the entire cost of installation and maintenance of the illumination devices. (Findings from OPUC's studies were used as a guide in some of these crossing illumination projects.) A railroad constructed and fully funded one illumination project, including electrical power and maintenance costs.

Illumination has been installed at 34 crossings to date; criteria developed by OPUC were used. GCPA was the major source of funding (75 to 90 percent) for all but one of these projects. The road authority paid 5 percent, and the railroad paid the remaining 20 or 5 percent. One project was funded 90 percent by federal Section 130 funds and 10 percent by GCPA. Maintenance costs were divided equally by the road authority and the railroad. In most cases, the road authority pays the monthly bill to the supplier of electrical power, and bills the railroad for its share annually. A few crossings are maintained by an electrical contractor. Table 1 lists the 34 crossing illumination projects by year of completion.

ORIENTATION OF LIGHTS

At first, it was difficult to convince road authorities and electrical companies that luminaires should be aligned toward the railroad tracks instead of the roadway. Several meetings were held to demonstrate that aligning the luminaires toward the railroad tracks increased the effectiveness of the illumination. Eventually, all parties agreed that the luminaires were more effective if they were aligned toward the track. As shown in Table 1, a higher percentage of the installations complied with the 1-ft-c standard for illumination when the luminaire faced the railroad tracks.

TABLE 1 CROSSING ILLUMINATION PROJECTS BY YEAR OF COMPLETION

Year	No. Tracks	Luminaires Facing Railroad	Luminaires Facing Road	Readings Taken To Date	Av % of the 1 Ft-Candle Requirement
1984	1	4		1	100
1985	1		2	4	85
1985	1	1	1	3	70
1985	1		2	3	51
1985	2		2	3	93
1985	1		2	3	97
1986	1	2		3	100
1986	3	2		3	89
1986	2	2		3	87
1986	1	2		3	93
1986	2	2		3	77
1986	2	1	1	3	53
1986	1		2	3	48
1986	1		2	2	93
1986	2		2	2	80
1986	1		2	2	100
1987	1		2	3	99
1987	1	1	1	4	98
1987	1	2		2	94
1987	1	2		3	96
1987	1	2		1	100
1988	1	2		2	100
1988	1	2		2	100
1988	1	2		2	100
1988	1	2		1	100
1988	1	2		1	100
1988	1	2		1	100
1988	1	2		1	100
1988	1	2		1	100
1988	1	2		1	100
1988	1	2		1	100
1989	1	2		1	100
1989	1	2		1	100
1989	1	2		1	100

Twenty-five light readings were taken at nine crossings at which the luminaires faced the road. The readings showed a 48 to 100 percent compliance rate with the 1-ft-c requirement. The average compliance rate was 82 percent.

Ten readings were taken at three crossings at which one luminaire was directed toward the track and the second one was directed toward the road. These readings showed a 53 to 98 percent compliance rate, with an average rate of 73 percent.

Thirty-six readings were taken at 20 crossings at which the luminaires were directed toward the railroad. The readings showed a 77 to 100 percent compliance rate, with an average rate of 96 percent.

PROBLEMS ENCOUNTERED

Where possible, the luminaires were mounted on existing utility poles. Occasionally, railroad pole lines or heavy power lines or both interfered with the preferred location for luminaire poles. If the existing poles were not long enough, luminaires were installed in each crossing quadrant to provide adequate illumination.

Two crossings were vandalized. The problem was resolved at one crossing by education and increased police patrols.

"Light-out" problems (luminaires not working properly) were encountered at approximately 2 to 3 percent of the crossings. They were found primarily during OPUC staff routine field testing of the illumination devices.

SPECIFICATIONS

For single-track crossings, poles were located approximately 25 ft from both the road and the centerline of the railroad track. Two-hundred-watt high-pressure sodium luminaires were placed at least 30 ft above the top of the rail on 6- to 16-ft-long arms. If a railroad signal system was involved, full cutoff luminaires were used.

For multiple-track crossings, 400-watt high-pressure sodium luminaires were placed at least 40 ft above the top of the rail. If a considerable distance separated the tracks, it was desirable to install a luminaire between the tracks. Semicutoff luminaires were used because they spread the light over a larger area of the crossing. This treatment was needed particularly at crossings of three or more tracks and those with severe angles of intersection.

COSTS

Initially, OPUC staff estimated the installation cost of illumination to be about $2,000 per crossing. (This included the two wooden poles with two 200 = watt high-pressure sodium luminaires on arms 6 to 16 ft long.) The average installation cost for the 34 crossings was $1,931. The most expensive installation was $9,384, and the least expensive one was $386. The most expensive project involved digging a ditch approximately 1 mi long to provide electrical power to the site. Monthly maintenance costs averaged about $15 per luminaire/pole. Maintenance costs for publicly owned utilities were slightly less.

FUTURE PROJECTS

OPUC staff prepared and distributed two lists of crossings that met the minimum criteria for illumination. The lists were provided to various public road authorities for their consideration. Without their input and cooperation, additional illumination devices may not be installed at other grade crossings in Oregon.

ACCIDENT HISTORY

Does using illumination at crossings reduce train-vehicle accidents? Based on the OPUC experience, the answer is yes. Before 1985, 18 train-vehicle accidents occurred at 13 crossings during the hours of darkness. Since the illumination program began, three train-vehicle accidents have occurred at two crossings during the hours of darkness.

Because the sample is small, it is statistically invalid to draw many definite conclusions. However, on the surface, it appears that safety at grade crossings can be improved by using illumination devices that meet the minimum criteria described here. Illumination is another tool that can be used to help reduce train-vehicle accidents at grade crossings that meet specific criteria.

CONCLUSIONS

Crossing illumination has been accepted with enthusiasm by local citizens and some public road authorities. Illumination provides an opportunity to improve safety at crossings that might otherwise not be addressed. The cost of installing automatic protective devices at grade crossings is prohibitive at many locations. Illumination has provided an effective low-cost alternative for improving crossing safety. Such medium-to-low-level priority crossings might not qualify for current dedicated funding programs.

Through experimentation and study, OPUC staff have found an acceptable standard for crossing illumination. Illumination is not appropriate for all crossings (e.g., those without regular nighttime train movements). It should only be applied in cases in which specific criteria have been met.

The information gathered about crossing illumination is a result of the cooperation of local road authorities, railroads, utility companies, and OPUC staff. The staff has been fortunate to work with parties who were willing to experiment in finding an answer.

Judging a Ship's Lateral Position and Direction of Motion with Simulated Visual Aids to Navigation

KEVIN LAXAR, S. M. LURIA, AND MARC B. MANDLER

An appropriately designed parallax (two-station) range allows a mariner to accurately determine a range line—the correct path to steer a vessel—at great distances. Less expensive alternatives to parallax ranges are desirable, and many ideas for single-station ranges have been proposed, but mariners' abilities to establish range lines with them have not been measured. The present work quantified the sensitivity of three different range systems and determined how much information can be provided by a range in order to achieve a criterion performance level. These systems use (a) temporal characteristics, (b) spatial representation, or (c) color changes of the signal to represent changes in lateral position. Range systems were simulated either opto-mechanically or on a high-resolution computer display system. The ability of the mariner to determine both lateral position in a channel and direction of motion across a channel was assessed psychophysically for each range. The performance was compared with that obtained with a parallax range. This allowed quantification of performance and evaluation of the implications of replacing parallax ranges with the single-station ranges.

The U.S. Coast Guard uses a visual method, the parallax range beacon, to indicate to a vessel's operator the correct path or range to follow along such navigation channels as approaches to harbors and within rivers. For nighttime use, this consists of a pair of lights positioned on the range axis with the farther light higher than the nearer one (Figure 1). The vertical alignment of the lights indicates that the vessel is positioned on the range's longitudinal centerline, or range axis, and any deviation from this course is readily apparent.

Although effective and easy to use, such aids are expensive because the more remote range light is typically located on shore, requiring the purchase, construction, and maintenance of the site. An alternative single-station range indicator—that is, a device located at one site—is therefore desirable.

In this study, visual performance was compared for four types of parallax ranges and three types of single-station ranges under similar laboratory conditions. In particular, how well observers could judge when they were on and off the range axis and when they were moving toward and away from the range axis were examined. Measurements were made at different lateral positions in the channel to map the sensitivity of the range system across the width of the channel. The objectives were to determine which range systems provide information adequate for navigation and provide guidance to the engineer designing range systems.

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Interim results are presented here; final results will be reported in a subsequent publication (*1*). Further details of the experiments can be found in the reports referenced at the beginning of each of the following sections on the various simulated display types studied. The experiments on the color-coded range system were incomplete at the time of this report. Results can be found elsewhere (*2*).

PARALLAX RANGES

Our baseline performance was the observers' ability using parallax ranges to judge their motion toward or away from the range axis (dynamic simulations), and whether they were on or off the range axis (static simulations) (*3*).

Method

Observers

Volunteers from 23 to 59 years of age participated in the experiments. All had normal color vision and 20/25 or better visual acuity, with correction if required. Most were experienced psychophysical observers. In these parallax experiments, 13 observers participated in the dynamic simulations, and 4 of them also participated in the static simulations.

Apparatus

The range configurations were simulated on a Ramtek 9400 high-resolution color display system driven by a DEC VAX minicomputer. Observers responded using an auxiliary key pad.

Displays

Four types of parallax range indicator lights, discussed next, were simulated dynamically. The first two types are in use; the latter two have been proposed as alternatives.

Two-Point Fixed This range display consisted of two lights that were always on and vertically aligned when viewed from the center of the channel. The lights were 0.6 arc min in diameter and separated by 4.0 arc min when aligned (Figure

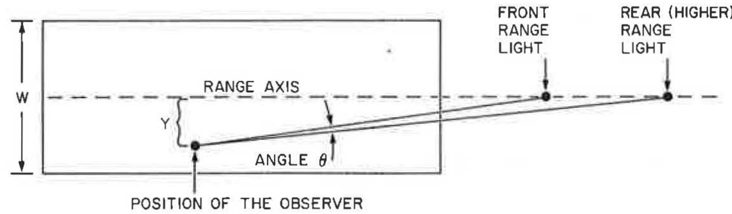

FIGURE 1 Top view of a parallax range: *W*, channel width; *Y*, distance of observer from range axis; θ, horizontal component of the angle between the lights.

2a). The vertical separation approximated the angle specified by the U.S. Coast Guard for affording optimal sensitivity in perceiving lateral position (*4*). When viewed from off center, the lights were not vertically aligned, and the misalignment increased with increasing distance from the center of the channel.

Two-Point Flashing The second display was similar to the two-point fixed except that the two lights flashed continuously. The upper light was on for 3.0 sec and off for 3.0 sec, and the lower light was on for 0.3 sec and off for 0.7 sec (Figure 2b).

Extended Source This range display consisted of two bars of light, 0.3 arc min × 6.0 arc min, oriented vertically with no separation between them, and they were always on (Figure 2c). As with the spots of light, they were in vertical alignment only when seen from the center of the channel.

Path Indicator The fourth type of display consisted of a column of lights (Figure 2d). The center light, larger than the others, was in alignment with the column only when viewed from the center of the channel. This type of display, oriented horizontally, is typically used as a glide slope indicator on aircraft carriers. It was oriented vertically so that lateral position instead of elevation was indicated. Unlike the device used on aircraft carriers, which shows five discrete elevations, this display provided a continuous change in lateral position to determine if the enhanced display improved performance. If implemented, it might be constructed as a single-station range device using Fresnel lenses as on aircraft carriers.

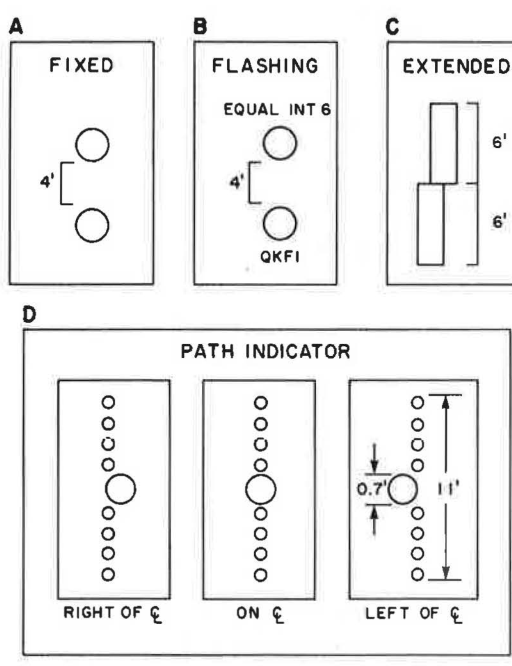

FIGURE 2 Four parallax range light configurations.

Procedure

For the static experiments, only the two-point and extended-source ranges were simulated. Observers were seated 6 m from the computer monitor and were given 5 min to adapt to the dark. The monitor screen subtended visual angles of 2.4 degrees high × 3.3 degrees wide and was uniformly illuminated to 0.003 cd/m^2, equivalent to the night sky with a partial moon. The white stimuli, at a luminance of 100 cd/m^2, were centered on the screen. The luminance level was imposed by hardware constraints. The testing room was otherwise dark.

Static Thresholds These experiments were similar to the visual acuity experiments of Westheimer and McKee (*5*). The static thresholds, here and throughout this study, were measured with the method of constant stimuli. In separate experiments, either the two-point or the extended-source range was presented with the lower light in one of nine positions up to 37.1 arc sec (0.62 arc min) to the right or left of the upper light. The stimulus positions were chosen to encompass the range whose extreme values could easily be judged by the observers as off axis. The stimuli were presented in random order for 0.2 sec once every 4 sec. The observer pressed one of two buttons on the keypad to indicate a left or right relative position of the lower light. Each position was presented randomly 30 times in two 270-trial sessions that lasted 18 min each, and the computer recorded each response.

Dynamic Thresholds These thresholds were measured with the method of limits throughout this study. For each trial, a pair of range lights was displayed in a configuration corresponding to a view from some distance off the range axis. After 1 to 5 sec, the bottom light began to move slowly to the right or left, simulating a vessel's motion across the channel. As soon as the observer could correctly judge the direction of motion, he or she pressed a button corresponding to that direction. When the correct button was pressed, the angular distance that had been traversed by the lower light was recorded by the computer. Trials were separated by a 2-sec interval. Errors were recorded, and those trials were rerun later in the session.

Eleven starting positions, up to 6.2 arc min right and left of center, were chosen randomly. Situations were simulated in which the mariner was off the centerline by different amounts when first viewing the display, and the change in distance from centerline that is required before a change in the display can be detected was calculated. The lower light moved at 9.3 arc sec^2. For typical channel configurations, this corresponded to a speed of 2.6 to 11.5 knots across the channel. This was so imperceptibly slow that judgments were based on the position of the lights at some time after the motion started.

Performance was measured in a single experimental session. This consisted first of 42 practice trials. Next, trials at each starting position were presented in random order in both directions. This was repeated over three blocks. The session thus comprised 66 trials and lasted about 50 min.

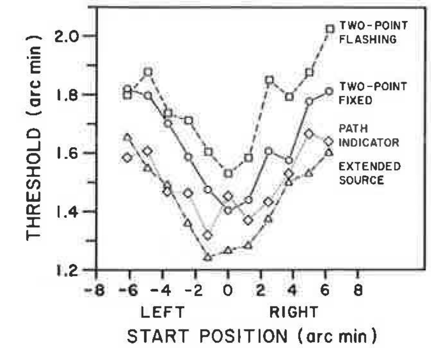

FIGURE 3 Motion thresholds for four parallax range light configurations (in all references to thresholds, lower thresholds indicate greater sensitivity, or better performance).

Results

Static Thresholds

Data from the four observers were combined, and probit analyses were conducted on the 2,160 trials from both the two-point and extended-source range configurations. With chance performance represented by the 50 percent probability level and certainty represented by 100 percent, a probability of 95 percent correct responses was chosen for the practical purposes of this study. With the two-point range, observers could judge when they were off the range axis by 30.7 arc sec (0.51 arc min). With the extended-source configuration, the mean accuracy was 33.2 arc sec (0.55 arc min). The difference between the two range configurations was not significant, $t(3) = 0.80$, $p > .10$. Additional practice and a less conservative criterion probability level would likely have made the performance of these observers approach the 5 to 10 arc sec acuity found by Westheimer and McKee (*5*).

Dynamic Thresholds

Figure 3 shows the average thresholds for detecting motion both to the left and right of start position for the four range displays. Threshold is the average deviation from the start position required by the observers to correctly judge the direction of motion for that range.

A repeated measures analysis of variance (ANOVA) was computed on the deviations for the following factors: 4 range indicator configurations × 2 directions of motion (to the right or left) × 11 start positions × 13 subjects. Thresholds varied significantly with range configuration, $F(3,36) = 3.46$, $p < .05$. A Newman-Keuls test showed a significant difference between only the extended-source and the two-point flashing range configurations ($p < .05$), however.

The effect of the start position was also significant. Thresholds are smallest for start positions at or near the range axis (start position of 0.0) and increase as the start position distance increases left or right from center. This means that observers can easily determine whether they are moving toward or away from the range axis when near the axis, but they require a greater change in lateral position to correctly judge their direction of motion when off the range axis.

The right-left direction of motion effect was not significant. However, a significant interaction was found between direction of motion and start position, $F(10,120) = 15.36$, $p < .001$. This interaction defines the direction of relative motion (DRM) effect (toward or away from the range axis), which was significant in separate ANOVAs for all four range configurations. This DRM effect indicates that thresholds for judging motion toward the range axis are different from thresholds for motion away from the range axis. Figure 4 shows an example of these results for the two-point fixed range. Observers were better at judging changes when the direction of relative motion was toward the range axis than when it was away, by an average of 0.31 arc min. Results for the other types of parallax displays were comparable.

Four of the 13 observers had extensive experience in making fine perceptual judgments. To determine whether such experience had any effect on motion thresholds, their performance was compared with that of the entire group. The experienced observers had thresholds averaging 0.5 arc min more sensitive than the entire group.

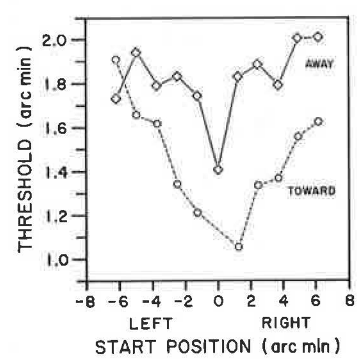

FIGURE 4 Thresholds for relative motion toward and away from the range axis for the two-point fixed range.

Errors—that is, when the observer responded with the wrong direction of motion—were analyzed in a corresponding manner to that for motion thresholds. Table 1 shows that the two-point flashing range produced almost twice as many errors as the other configurations. A four-way ANOVA showed a significant effect on errors for range configuration $F(3,36) = 3.44$, $p < .05$. A Newman-Keuls test showed that the two-point flashing range was significantly different from the other three configurations, $p < .05$, which were not significantly different from each other.

The effect of start position was also significant [$F(10,120) = 3.68$, $p < .001$]. The error data for all range configurations combined are shown in Figure 5. As with judgment of motion, the best performance was near the on-axis position and became increasingly poor as the off-axis distance increased. Interestingly, direction of relative motion toward or away from the range axis had no effect on error rate, in contrast with the significant effect it had on judgment of motion.

ROTATING BEAMS SINGLE-STATION RANGE

This proposed range indicator displays a horizontal triplet of lights that appear to flash simultaneously when viewed from the channel centerline; when the vessel is to the right of centerline the right light would appear to flash first, and when to the left of centerline, the left light would appear to flash first (*6*). This asynchrony would alert the mariner that the vessel was off course and in which direction. The course could then be altered until the lights were again flashing simultaneously.

TABLE 1 MEAN ERROR PERCENTAGES BY PARALLAX RANGE CONFIGURATION

Range Configuration	Direction of Relative Motion: Toward	Away	Mean
Two-point fixed	9.5	12.4	11.1
Two-point flashing	17.1	18.0	17.5*
Extended source	6.7	10.3	8.6
Path indicator	4.4	13.3	9.2
All			11.6

*Significantly different from all others, which were not significantly different from each other.

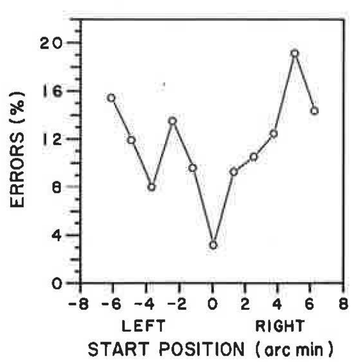

FIGURE 5 Mean percent errors for four parallax ranges combined.

To design such a beacon, the smallest interval at which most viewers can perceive temporal order with reasonable reliability must be determined. Earlier studies found intervals ranging from as little as 3 msec (*7*) to 30 msec (*8*) for binocular viewing, depending on the stimuli used. To approximate point source lights under night viewing conditions, the following experiment was conducted (*9*) to simulate this single-station range indicator.

Method

Apparatus

The three flashing lights were produced by three cylinders with apertures, rotating about separate light sources. Figure 6 illustrates the operation of the apparatus. The left beacon, with two beams, rotates counterclockwise at a given speed. The center beacon, with one beam, rotates clockwise at twice that speed. The right beacon, with two beams, rotates clockwise at the same speed as the left beacon. All three beacons therefore flash at the same rate. The interval between sequential flashes increases with distance from range axis. To simulate angles off the centerline, movable apertures were placed in front of the beams (instead of rotating the apparatus or moving the observer). At the viewing distance of 6.1 m, the lights were 0.78 degree (47 arc min) apart and subtended 0.01 degree (0.6 arc min) visual angle. The lights were flashed once every 2 sec (0.5 Hz). Their luminance was 230 cd/m^2, and the flash duration was about 50 msec. The experiments were conducted in a dimly lit room.

Procedure

Ten observers were given several practice sessions before the start of the study, and 2 min for adaptation to the ambient illumination before each session.

Static Thresholds The observer viewed the set of lights at either 0 degrees (centerline) or at various viewing angles. The magnitude of the angle needed for a correct judgment of the temporal order (left light first versus right light first) was measured. A given angle of view was set and the flashing lights exposed until the observer made a judgment. The lights were occluded while a new angle of view was set, and so on.

Dynamic Thresholds The minimal amount of change in the viewing angle of the flashing lights that the observers could perceive was measured. Starting with randomly varied viewing angles of 0 (simultaneity), 1, 2, 4, or 6 degrees to the right or left of centerline, the difference threshold was measured for both increasing and decreasing viewing angles. For each trial, the display was exposed and the viewing angle remained constant for a random period of 5 to 10 sec, after which the angle was changed at the rate of 5 degrees/min. The observer

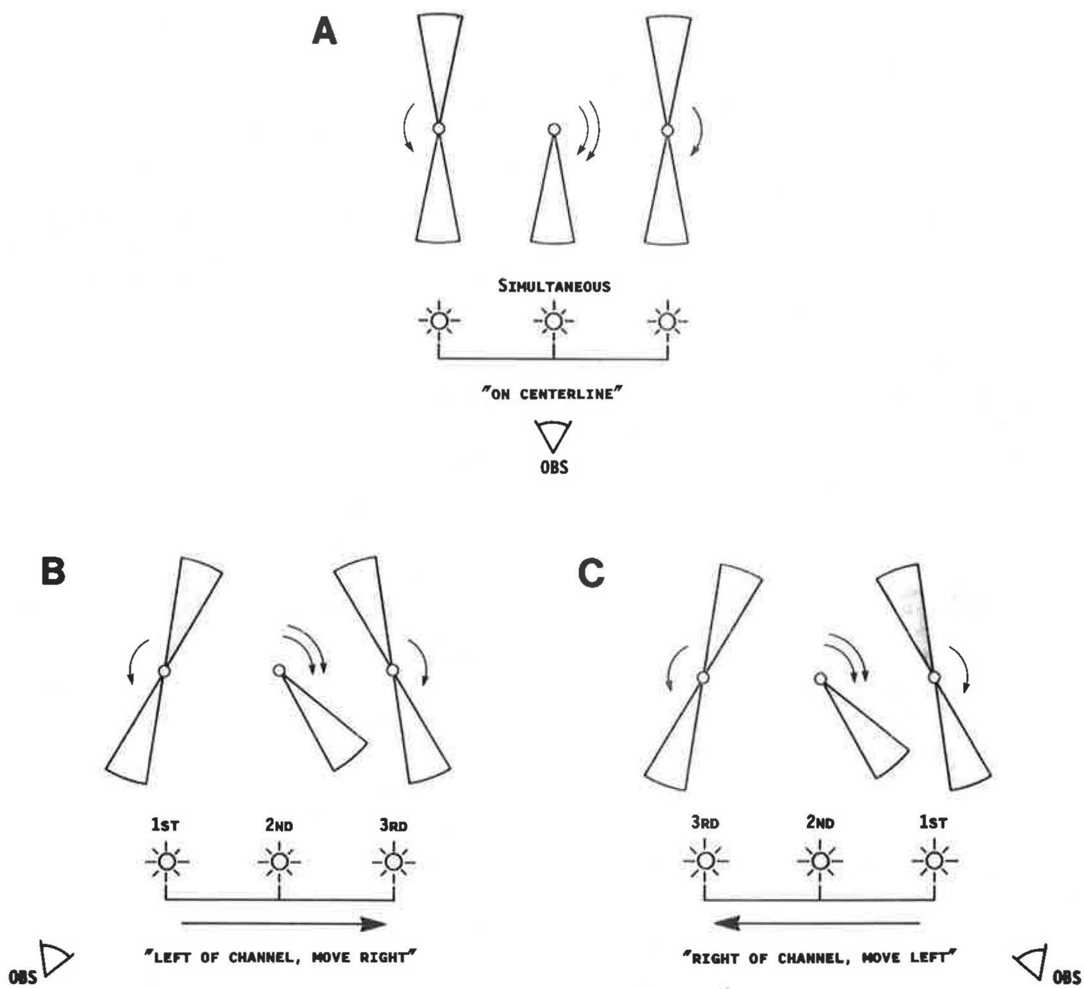

FIGURE 6 Operation of the sequential beacons: (a) when viewed from range axis, beacons flash simultaneously; (b) when viewed from left of range axis, left beacon is seen first, followed by center beacon and then right beacon; (c) when viewed from right of range axis, right beacon is seen first, followed by center and then left.

reported when a change in the flash pattern was detected and whether the change was toward more or less simultaneity. Incorrect responses were not recorded, but the trial was repeated at some random time later in the session.

Results

Static Thresholds

Mean thresholds were calculated to determine the viewing angle at which the observers correctly identified the left-right direction of temporal order. A probit analysis was used to compute the 95 percent correct threshold. This resulted in a mean temporal interval of 8.4 msec between the flashes of the left and middle beacons, or 42.7 arc min (SD = 21.4 arc min) of visual angle from the centerline position.

To further study this type of range display, several parameters were varied. Thresholds were measured using two flashing lights instead of three. Thresholds were not significantly different, although the variability with the two lights was greater. Again using just two lights, no significant differences in thresholds were found when the lights were separated by only 16 arc min of visual angle rather than the original 47 arc min. Thresholds were significantly worse, however, when the luminance of the lights was decreased in three steps from the original level of 230 cd/m^2 to 0.65 cd/m^2 (*10*).

Using the three-light display, performance was measured when the display was flashed at twice the flash rate (once per second) and at half the flash rate (once every 4 sec) with that presented in the previous experiments (once every 2 sec). The temporal interval threshold to identify temporal order remained constant at about 5.6 msec for all flash rates, but the angular deviation from centerline at which the observers could perceive nonsimultaneity decreased proportionally as flash rate decreased. When flashed at the slowest rate, sensitivity was doubled in comparison with the figures given above, a substantial improvement in performance.

An additional experiment showed that the temporal interval threshold, and therefore the viewing angle, decreased when the lights were defocused by putting lenses up to +2 diopters in front of the observers' eyes (*11*). Performance improved nearly twofold with the blurred image.

Dynamic Thresholds

Figure 7 shows the mean difference thresholds both in terms of the change in the viewing angle and in the temporal interval for each of the five starting positions. The standard deviations of these values were on the order of 35 arc min. The data show means for only 9 observers because one observer found it too difficult to do the task at the 4- and 6-degree conditions.

As the angle of the starting position from the centerline increased (and, therefore, the magnitude of the temporal interval between flashes increased), it generally became more difficult for the observers to detect a change in the flash pattern. The effect of the start position was highly significant according to the Friedman Analysis of Variance by Ranks, ($\chi r_2 = 11.93$, $p < .01$). The difference between "toward" and "away from" simultaneity was not significant.

The curves are, of course, not monotonic. The thresholds drop at approximately 1 and 2 degrees, after which they rise continuously. One explanation seems evident. There is a range of perceptual simultaneity, temporal intervals around simultaneity that the observer cannot discriminate. When this range is exceeded the observer can detect nonsimultaneity, which for most observers occurs at a viewing angle of between 1 and 2 degrees. If the starting position is 1 degree off center, the resulting temporal interval is typically too small for the observer to detect. However, only a small increase in temporal interval is required to detect that the lights are no longer simultaneous. If the starting position is simultaneity, then a larger change is required to exceed the range of perceptual simultaneity. If the starting position is 2 degrees off center, this is typically just outside the range of perceptual simultaneity. Thus, only a small decrease in temporal interval results in the observer readily reporting simultaneity. A much larger change is required if the temporal interval is increasing.

FREQUENCY ENCODED SINGLE-STATION RANGE

This proposed flickering or flashing light range display would indicate lateral position in the channel by varying the flash frequency, combined with chromatic information to indicate left or right side (Figure 8). When on the centerline, the navigator would see a steady light. As the vessel moved off the centerline, the navigator would see the light start to flash on and off, increasing in frequency with distance from the centerline. Moving to the right could be signalled by a flashing red light, and moving to the left by a flashing green light. The range centerline position could be indicated by a steady white light.

The basic question is, how well can observers discriminate the frequency of a flashing light? Earlier studies (*12–15*) found that over the range of 1 to 20 Hz, the difference threshold, Δf, was a monotonically increasing function of frequency, but results varied widely in the range of 0.01 to 2.4 Hz, depending on stimulus size and experimental procedure. None used a point source of light on a dark background or measured difference thresholds of a constantly flashing light as it slowly changed frequency, as would be the case with a flashing range indicator when a vessel traveled across the width of the range. The following experiment was therefore conducted (*16*).

Method

Apparatus

The light source was a diffused white beam that subtended a visual angle of 1.9 arc min at the 6 m viewing distance. Its steady-state luminance was 41 cd/m². The 50 percent duty

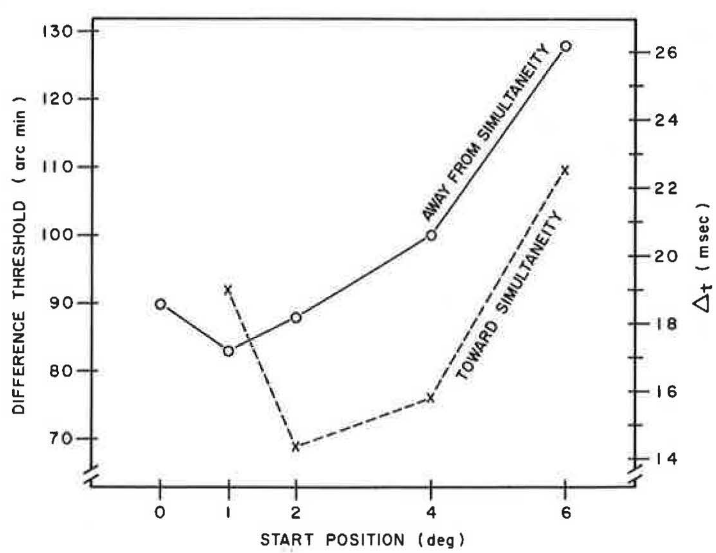

FIGURE 7 Rotating beams difference thresholds in minutes of arc of viewing angle and temporal interval, as a function of start position in degrees of off-center viewing; thresholds are shown for changes toward and away from simultaneity.

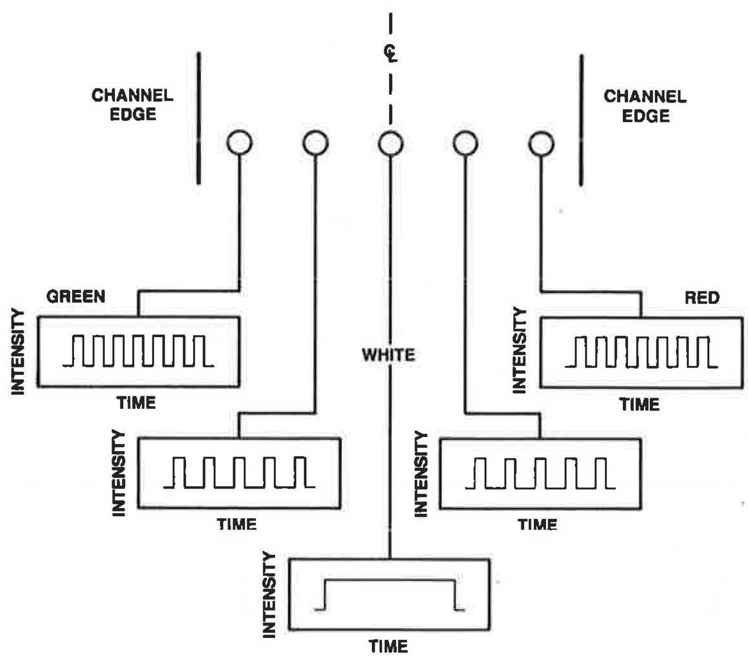

FIGURE 8 Frequency encoded range.

cycle of the light was modulated by a rotating half-sector disk mounted on a rheostat-controlled electric motor. By adjusting the speed of the motor, the light could be made to flicker at the desired frequency, which was calibrated by a Strobotac (General Radio Corp.). Five base frequencies were used: 0.5, 1.0, 2.0, 4.0, and 6.7 Hz.

Procedure

The observer sat in a dimly lit room and binocularly viewed the apparatus, which was set to one of the five base frequencies. The frequency was then slowly increased or decreased, at the rate of approximately 1 Hz in 30 sec, until the observer correctly reported "faster" or "slower," and the change in frequency was recorded. A minimum of three such thresholds was determined for both faster and slower flicker rates at each base frequency. Four observers participated. Only thresholds for changes in frequency, simulating a vessel's motion across a channel, were measured because it was assumed that a position on centerline would be displayed as a light that did not flicker. The distance from the centerline at which the light appeared to flash would be determined by the angle through which the steady light was displayed and the distance the observer was from it.

Results

The mean faster and slower frequency difference thresholds for all observers at each base frequency were calculated. Because the two thresholds were similar, their mean was calculated; the difference thresholds (Δf) and their standard deviations are shown as a function of base frequency in Figure 9. Difference thresholds increase nearly linearly as base frequency increased. The standard deviations also increase at the higher base frequencies. The results show that the observer's sensitivity to changes in frequency decreases as the frequency of the flashing light increases. This would mean that the mariner's sensitivity to lateral motion decreases as the vessel approaches the edge of the channel.

The mean difference threshold can be termed a just noticeable difference (jnd) in frequency. The number of jnds was summed up within the range of 0 to 6.7 Hz, resulting in 24 discriminable steps. The cumulative jnds are given by base frequency in Figure 9.

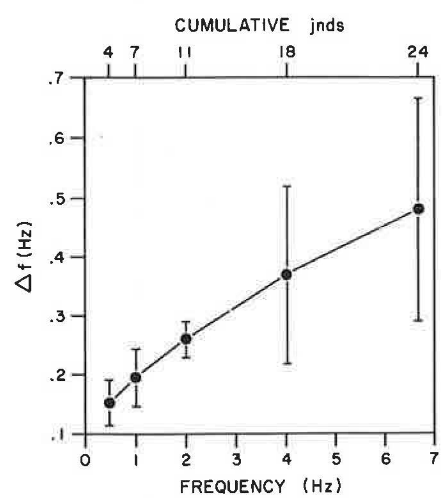

FIGURE 9 Frequency difference thresholds (Δf) by base frequency for four observers; error bars show standard deviations.

DISCUSSION OF RESULTS

Observer sensitivity for judging position in the channel depends on the type of range display, the starting point in the channel, and the direction of motion. The results have been presented thus far in terms of angular measures of sensitivity. To relate the measured deviation thresholds to accuracy of navigation it is necessary to convert the angular measures to distances in a given channel. The Commandant of the U.S. Coast Guard (*4*) has specified optimal limits for parallax range configurations, represented by a lateral sensitivity factor, *K*, calculated from the length and width of the range and the placement of the range lights. Design guidelines require that ranges have *K* factors between 1.5 and 4.5. A range with a *K* factor less than 1.5 will not change its alignment perceptibly with small changes in lateral position. A range with a *K* factor greater than 4.5 will change alignment too rapidly with changes in lateral position. In the following discussion, a range 152 m (500 ft) wide by 1,219 m (4,000 ft) long is assumed, with the near end of the range 610 m (2,000 ft) from the range beacon. This gives a *K* factor of 4.5 at the near end of the range and 1.5 at the far end and provides a basis for direct comparison of the various range displays. For a given *K* factor, thresholds are directly proportional to channel width, so the results are applicable to any range configuration.

Static Thresholds

The performances of the four types of range displays tested, at both the near and far ends of the channel, are compared in Figure 10. Relative performance is similar for both ends of the channel, with thresholds at the far end three times greater than those at the near end, because the distance from the beacon(s) is three times greater. The two-point fixed and the extended-source parallax displays are nearly identical, with a threshold of slightly less than 4.5 m around the range axis at the near end and about 13.5 m at the far end of the channel.

The rotating beam display appears to afford much less sensitivity than the parallax displays, with thresholds that are nearly twice the size. Results showed, however, that the thresholds would be halved when the lights were flashed at half the rate illustrated by these data, bringing the levels similar to those of the parallax displays.

The frequency coded display, on the other hand, shows much better sensitivity than any of the other range types. These figures are arbitrary, however, and depend on the design of the beacon. In this type of display the centerline would be indicated by a fixed-on beam, and with a departure from centerline, the beam would start to blink. Centerline sensitivity would therefore depend on the angle covered by the steady on-center beam. The data shown here, 1.1 m at the near end and 3.2m at the far end, are based on the 24 jnds within the range of flash frequencies tested, as discussed in the following section.

Dynamic Thresholds

Figure 11 shows motion thresholds for the four types of parallax and two types of single-station range displays, on-axis and at the edge of the channel. The results are given for the far end of the channel ($K = 1.5$). Thresholds for the near end of the channel ($K = 4.5$) are one-third the size shown in Figure 11. Overall, the extended source is the best of the parallax range displays, followed by the path indicator. At the far end of the channel, the extended source, at 30.9 m sensitivity on axis, was 4.5 m better than the currently used two-point fixed-on display. At the channel edge, the extended source was 4.9 m better.

Performance was significantly better with motion toward the range centerline than away for parallax range displays. The mean difference of 0.31 arc min shown for the two-point fixed range display in Figure 4 is equivalent to having sensitivity 2.6 m better at the near end of the channel and 7.9 m better at the far end. Results for the other types of parallax range displays are comparable. This means that with such displays, mariners are less sensitive to motion when approaching the edge of the channel than when moving toward the centerline, perhaps contrary to what a range indicator should be capable of displaying.

The greater accuracy found with the group of highly experienced observers, 0.5 arc min, is equivalent to 4.3 m at the near end of the channel and 12.7 m at the far end. This suggests that with training or experience, performance can be improved for a variety of range light configurations.

The single-station rotating beam display shows higher thresholds than the others, at 47.9 m on-axis and 42.1 m at

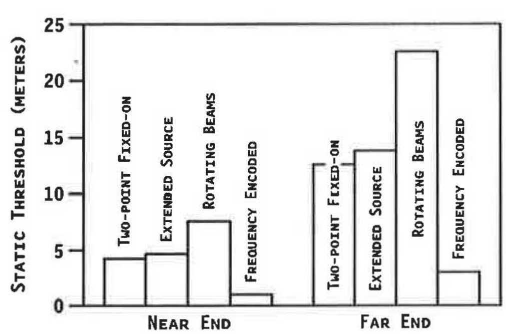

FIGURE 10 Thresholds for perceiving on- or off-range centerline, for two parallax and two single-station range displays at the near and far ends of the channel.

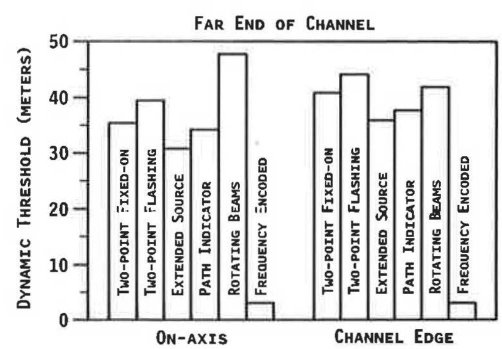

FIGURE 11 Thresholds for perceiving motion across the channel width for four parallax and two single-station range displays on the range axis and at the edge of the channel.

the channel edge, at the far end of the channel. When the lights were flashed at half the rate, sensitivity was increased twofold for static thresholds. Although motion thresholds were not measured, it is reasonable to assume that sensitivity to motion also would be greatly increased at slower flash rates. This could make the rotating beam display as good as, or better than, the parallax displays for static thresholds. The dynamic conditions would probably still remain difficult for the observers.

The frequency coded display appears to afford superior sensitivity. Based on the 24 jnds found between 0 Hz and 6.7 Hz, if this range of flash frequency were displayed across each side of the 152 m (500 ft) channel width (one side red, one side green) at the far end of the range (Figure 12), each half would contain a 0 Hz segment around the range axis plus 23 jnds, 1 + 2*(23) = 47 jnds across the channel width. If equally spaced, these would provide a sensitivity of 3.2 m (10.6 ft) perpendicular to the range axis. At the near end of the range, the same angular display would subtend 50.8 m (167 ft), with a sensitivity of 1.1 m (3.6 ft). Extrapolating to a flash rate of 20 Hz would provide an additional 16 jnds on each side if the display were to cover the full channel width at its near end, as shown in Figure 12. This would afford a sensitivity of 3.2 m (10 ft) at the outside segments of the channel.

Care must be taken in interpreting the results of the frequency coded display, however. Many factors affect the perception of flicker and could influence the frequency difference thresholds and alter the conclusions. These factors include the luminance, size, and color of the light, the duty cycle, waveform, and amplitude of flicker, and the background luminance. Operationally, factors such as atmospheric conditions and sea state could decrease an observer's sensitivity, thereby degrading performance.

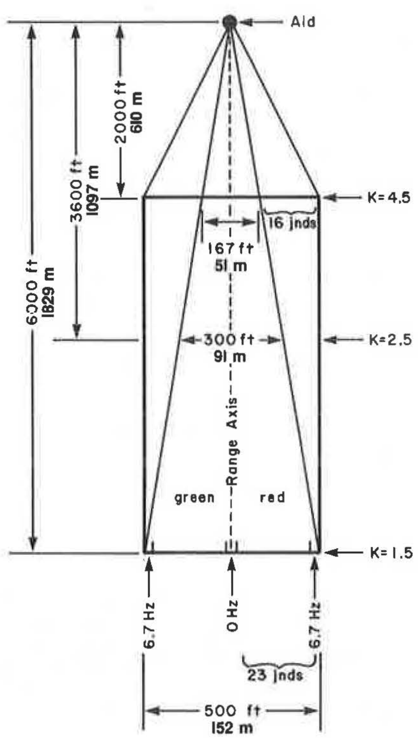

FIGURE 12 Single-station frequency coded range display on an assumed range, showing flash frequencies and jnds; *K* is the range sensitivity factor for a parallax range.

Not evident here is the uncertainty the observers expressed in judging changes in flash rate. Figure 9 shows the large standard deviations in frequency difference thresholds. This would tend to further worsen sensitivity and increase uncertainty as the observer approached the edge of the channel. The sensitivity afforded by an operational frequency coded range indicator may be considerably poorer than that shown here.

Summary

Four different current and proposed parallax range indicators and two types of proposed single-station range indicators were compared. Examination of a third type of single-station range indicator is under way. Parallax ranges have been used successfully for many decades, but results found here show that equally good performance might be obtained with single-station range indicators, which may cost less. All range indicators, however, showed poorer sensitivity and increased uncertainty of judgment as the observer approached the channel edge. These results, then, provide a basis for conducting field tests for further determination of the adequacy of single-station range indicators.

ACKNOWLEDGMENT

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Low-Visibility Lighting Criteria for Airports and Roadways

Robert E. Lambert and Seward E. Ford

The purpose of this paper is to present basic visibility information and criteria that are used for ground navigation of aircraft during low-visibility conditions. The information presented is also applicable to automobile and truck navigation and guidance in situations in which ground fog becomes a serious hazard to the motoring public.

The aeronautical ground lights located at airports are intended to provide visual approach and ground navigation guidance to aircraft pilots. Therefore, aeronautical ground lighting is considered to be a form of signal lighting.

The most important elements of aeronautical ground lighting are the configuration of the lighting system, the color of the lights, the beam coverage (vertical and horizontal), and the intensity of the lights under various conditions of visibility.

There are a number of configurations or signal patterns for lights at an airport. These basic patterns can be combined to provide visual guidance under a wide range of visibility conditions.

SIGNAL PATTERNS AT AIRPORTS

- Basic runway. White edge lights, green threshold lights, and red end lights.
- Runway for low-visibility landings. The items above, plus runway centerline lights, touchdown zone lights, and red filters in the last 3,000 ft of the centerline light and yellow filters in the last 2,000 ft of the edge lights.
- Taxiway lights. At most airports, low-intensity blue taxiway lights are used to mark the edges of taxiways in conditions of fair to good visibility under Visual Flight Rules (VFR). At big airports that must operate during low-visibility conditions, more intense green taxiway centerline lights are used for guidance. Taxiway centerline lights are about 200 cd average in green when used in low-visibility conditions.
- Approach lights. Several types of approach lights give directional and roll guidance during the final stages of a flight and assist the pilot during the approach to the runway.
- Light intensity. Each runway light has a specified beam intensity and distribution such that a well-balanced lighting system, free of optical illusion, is produced.
- Beam intensities and distribution. See Table 1. Complete specifications for all airport lights may be found in Annex 14, published by the International Civil Aviation Organization.

Crouse-Hinds Airport Lighting Products, 1200 Kennedy Road, Box 1200, Windsor, Conn. 06095.

VISIBILITY

Visibility on an airport is measured by or referred to as Runway Visual Range (RVR). It is defined as the distance one can see a light of 10,000 cd intensity. (This would be applicable to highway guidance).

There is an instrument that is located next to the runway called a transmissometer. This calibrated instrument is a light source of known intensity shining at a receiver 250 ft away. As the transmissivity through the atmosphere decreases, a signal change from the transmissometer is sent to a computer. The computer then records the transmissivity factor T of the atmosphere.

In addition to the transmissometer connection, a current to voltage transformer is connected from the computer to the high-intensity runway edge-light circuit. This circuit, along with the approach, centerline, and touchdown-zone lights, have 5 intensities (100, 20, 4, 0.8, and 0.2 percent) that provide for a range of brightness. This allows for changes to the light intensity settings for any visibility condition.

Because the computer records the intensity of the lights and the transmissivity of the atmosphere, it continuously calculates and will display an RVR number to air traffic controllers. The controllers can improve (increase) the RVR number by increasing the light intensity within the limits of the system. The controllers have tables of suggested intensity settings for various visibility conditions. Intensity can also be changed by pilot request. These data could easily be processed automatically to change light settings on a roadway.

LIGHT INTENSITY VERSUS VISUAL RANGE

The visibility of a signal light under various conditions can be calculated using Allard's Law. A graphical solution to Allard's Law is shown in Figure 1. These data, which were supplied by the U.S. Coast Guard, can be applied to almost any situation and are not restricted to airports.

It can be shown that the distance a signal can be seen is dependent on background luminance, transmissivity through the atmosphere, and intensity of the light.

For example (using Figure 1), a light of 1 cd intensity on an exceptionally clear night (T = 1.0) could be seen for 1.3 mi. However, under similar conditions in a haze (T = .30), the range of the same light would be reduced to 0.75 mi.

LIGHT INTENSITY VERSUS RVR

The intensity of runway lights in low-visibility conditions (i.e., those not shown in Figure 1), are shown in Figures 2 and 3,

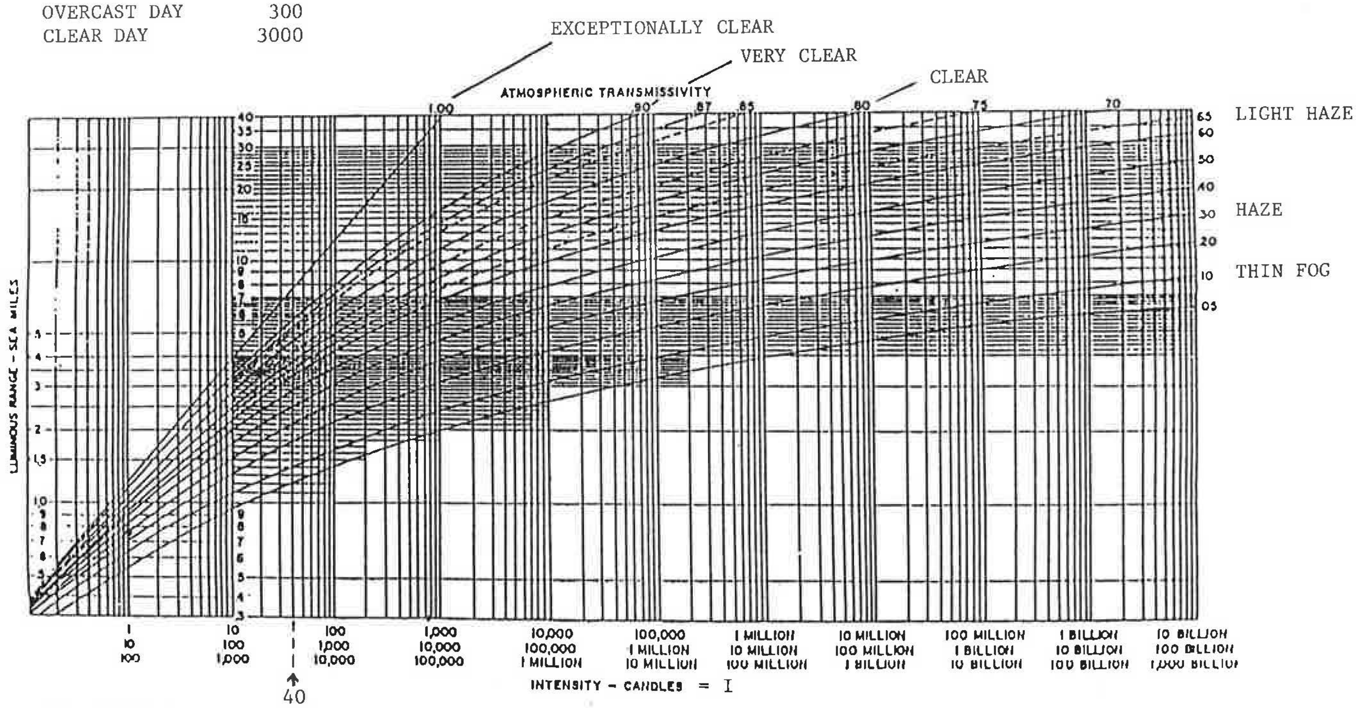
TABLE 1 LIGHT CHARACTERISTICS FOR CATEGORIES I, II, AND III PRECISION APPROACH RUNWAYS

Light	Colour	Minimum Beam Coverage: Main Beam H	Main Beam V	10% H	10% V	5% H	5% V	Minimum average intensity in specified colours Cd x 10^3	Limits of Average Intensity Ratio	Angular Settings: Elevation (degrees)	Toe-in (degrees)
1	2	3	4	5	6	7	8	9	10	11	12
Approach centre line and crossbars	White	20	11	28	13	30	17	20	1.5-2 max.	8-5.5	0-2
Approach side row	Red	14	10	23	12	33	16	5	0.5-1	6.5 - 5.5	2
Threshold	Green	11	9	15	12	18	17	10	1.0 - 1.5	5.5	3.5
Threshold wing bar	Green	14	10	23	12	33	16	10	1.0 - 1.5	5.5	2
Touchdown zone	White	10	7	14	12	17	17	5	0.5-1	5.5	4
Runway centre line (15 m)	White/ Red	10	9	14	17	17	20	2.5	0.25-0.5	4.5	0
Runway end	Red	12	4.5	15	10	18	13	2.5	0.25-0.5	2.5	0
Runway edge (45 m runway)	White	11	7	15	12	18	17	10	1.0	3.5	3.5

BACKGROUND LUMINANCE

CANDLES/M^2

CLEAR MOONLIGHT	.03
TWLIGHT	3.
OVERCAST DAY	300
CLEAR DAY	3000



.67 — NONE
6.7 — MINOR
67 — CONSIDERABLE BACKGROUND LIGHTING

40
400
4000

ILLUMINATION AT THE EYE IN SEA-MILE-CANDLES

ALLARD'S LAW NOMOGRAM

A graphical solution of Allard's Law: $E = \frac{I\,T^D}{D^2}$ E = Illumance

With a fixed transmissivity T and background illumination E, the graph relates range D to effective intensity I. The three intensity scales indicate levels of background lighting.

FIGURE 1 Graphical solution of Allard's Law.

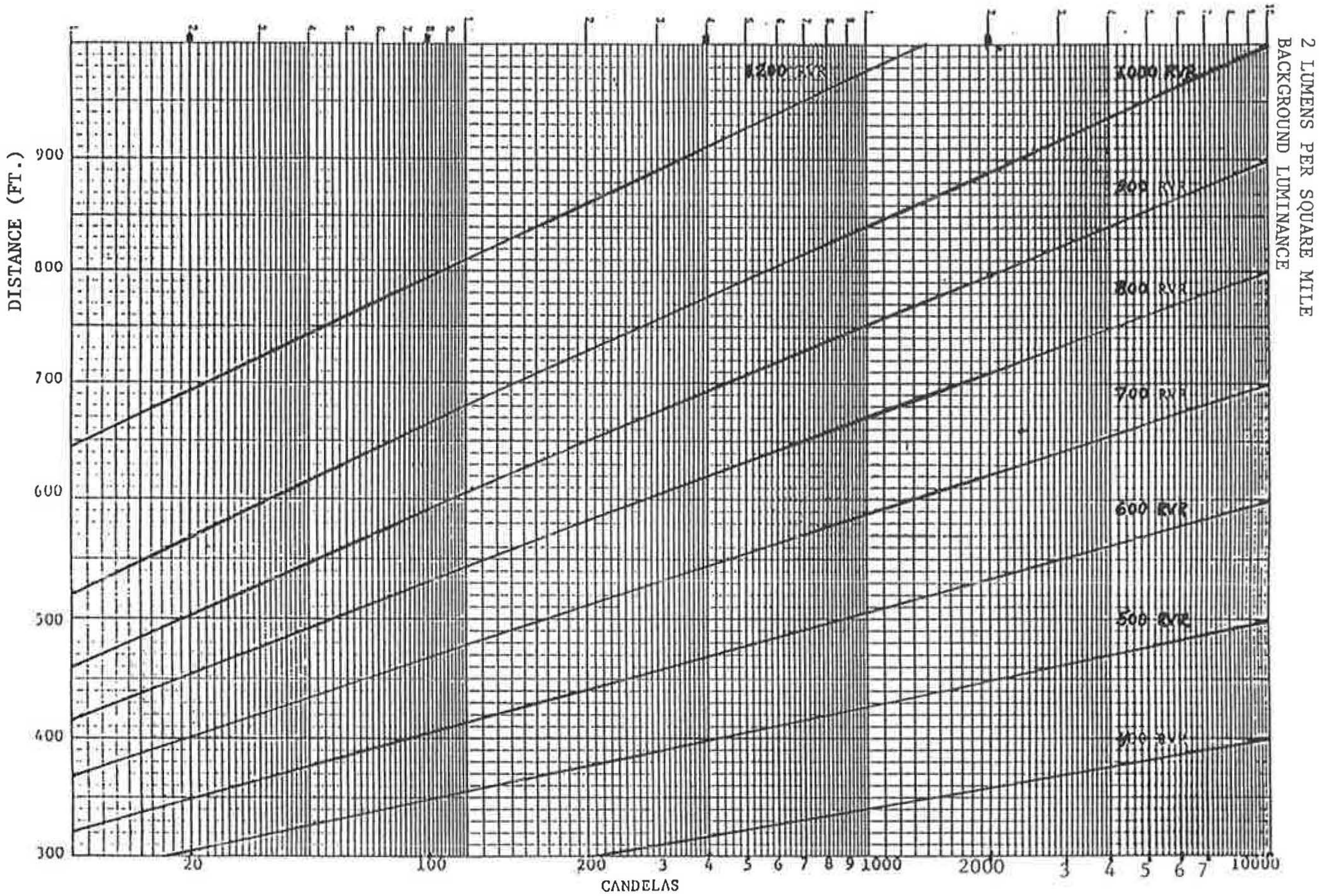


FIGURE 2 Visibility distance versus light source candle power at night.

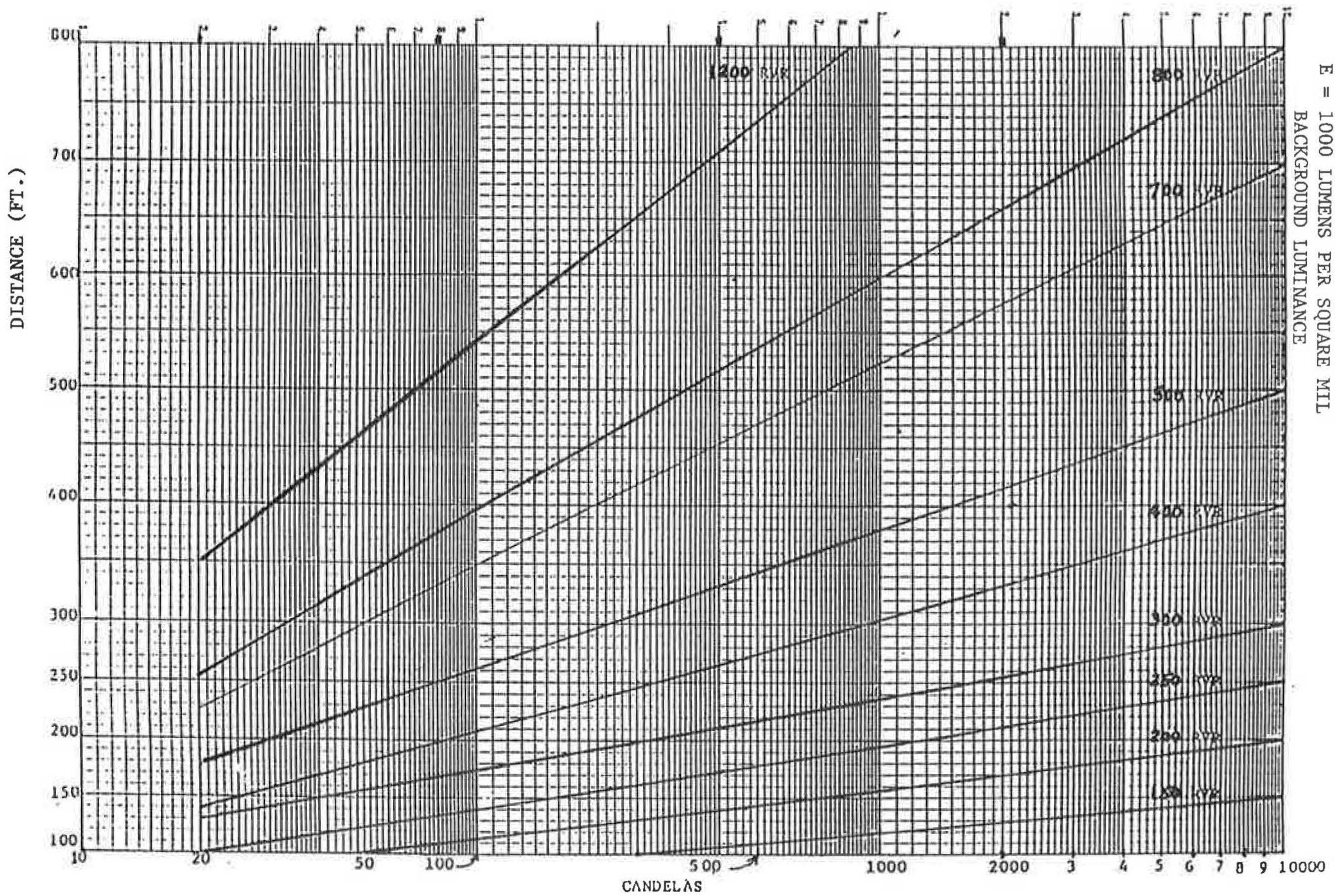


FIGURE 3 Visibility distance versus light source candle power during the day.

and Tables 2 and 3. Data were supplied by the Port Authority of New York and New Jersey. It must be remembered that the definition of RVR is based on a high-intensity light of 10,000 cd.

In the airport environment, visibility conditions are defined as follows:

- VFR. VFR apply when meteorological visibility (outside controlled airspace) is greater than 1 mi during the day and 3 mi at night. Cloud data are not included here because they are not applicable to the discussion.
- Category I. An instrument runway served by Instrument Landing System (ILS) and visual aids intended for operations down to a 60-m (200-ft) decision height and down to an RVR of 800 m (2,600 ft).
- Category II. An instrument runway served by ILS and visual aids intended for operations down to a 30-m (100-ft) decision height and down to an RVR of 400 m (1,300 ft).
- Category IIIA. This category is the same as Category II except RVR is 200 m (650 ft), with no minimum decision height and visual aids used during the final phase of landing.
- Category IIIB. RVR is 50 m (160 ft), with no minimum decision height and no visual aids used for landing.

In referring to Figure 2 and Table 2, it can be seen that an intensity setting at Step 4 (2,000 cd on the edge lights spaced at 200 ft) and (1,000 cd on the runway touchdown zone lights spaced at 100 ft) provides 800 ft of visibility at 900 RVR. At Step 5 (10,000 cd on the Edge Light and 5,000 on the Touchdown Zone Lights) the visibility is increased to 900 ft. In

TABLE 2 VISUAL RANGE UNDER LOW RVR CONDITIONS AT NIGHT

INTENSITY OF SOURCE (CANDELAS)	VISUAL RANGE OF SOURCE (FEET)					
	150'	200'	250'	300'	400'	500'
1	75	97	118	133	178	216
10	92	122	149	177	230	282
30	102	134	165	196	256	315
100	112	147	182	217	285	352
300	121	159	198	236	312	387
1,000	131	173	216	258	342	425
3,000	140	186	232	278	369	460
10,000	150	200	250	300	400	500
100,000	170	227	285	343	459	576
1,000,000	190	255	320	386	519	654

RVR IS THE VISUAL RANGE OF A 10,000 CANDELA SOURCE. THE ILLUMINANCE THRESHOLD IS 2 MILE CANDELAS.

TABLE 3 VISUAL RANGE UNDER LOW RVR CONDITIONS DURING THE DAY

INTENSITY OF SOURCE (CANDELAS)	VISUAL RANGE OF SOURCE (FEET)					
	150'	200'	250'	300'	400'	500'
1	43	52	60	68	80	89
10	66	83	99	114	141	165
30	78	100	120	140	176	210
100	92	118	145	170	218	263
300	105	138	169	200	259	316
1,000	120	158	196	233	305	376
3,000	134	178	221	264	350	434
10,000	150	200	250	300	400	500
100,000	181	243	306	370	500	631
1,000,000	212	288	365	443	603	767

RVR IS THE VISUAL RANGE OF A 10,000 CANDELA LIGHT. THE ILLUMINANCE THRESHOLD IS 1,000 MILE CANDELA.

other words, 5 times more light is needed to obtain another 100 ft of usable visibility. Similar examples can be given for daytime conditions from Figure 3 and Table 3.

AIRPORT DATA APPLICABLE TO ROADWAYS

The low-visibility systems used at airports are applicable to roadways under conditions of heavy fog when the transmissivity of the atmosphere falls below $T = 0.05$.

Such a condition takes place in Virginia on Afton Mountain on Interstate 64. The Virginia Highway Department, after trying many types and combinations of signs and reflectors, installed roadway inpavement (airport) lights to provide guidance for the motoring public under sudden and severe low-visibility conditions when clouds would suddenly cover the mountain and drivers would become instantly lost in the fog.

The Virginia Highway Department, in conjunction with the Virginia Highway Research Council, determined that inpavement runway lights were the only practical solution to this difficult and extremely dangerous highway guidance problem.

A system of lights using a modified runway touchdown-zone light and a detection system to determine fog density was installed on a 6.25-mi section of divided highway. The lights were located 200 ft apart on both sides of the road in a manner similar to runway edge lights. These inpavement lights have been in service for 10 years, and the results have been more than favorable.

The use of aeronautical ground lights for low-visibility roadway application is a subject that requires additional study to determine the effects of these navigational lights on drivers of various ages, optimum operating speeds, and whether other colors or patterns would improve the Afton Mountain installation. Recent accidents on highways during low-visibility conditions, when no lighting was available, indicate the potential for this kind of system.

OTHER POTENTIAL HIGHWAY APPLICATIONS

Another attribute of runway lights is that they are placed in a position in which the pilot or motorist is normally looking. For instance, inset red lights could be placed within a railroad crossing area instead of overhead. Even someone with poor eyesight or someone whose mind is on another subject could not help but see the red signal. In many applications, the intensity of inpavement lights for roadway applications could be on the order of 200 cd (similar to airport taxiway centerline lights) if the spacing were reduced to 25 ft. If spacing were greater, then a higher intensity would be required.

SUMMARY

In summary, Allard's Law is applicable to all signal visibility conditions. Special attention must be given to intensity, spacing, color, and patterns to provide the visual guidance needed for various conditions of vehicle operation by people 16 years of age and older.

With ever-increasing traffic, the problem of guidance in low-visibility conditions must be addressed if highway accidents involving scores of vehicles are to be avoided.