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

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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

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

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.

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

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 x	1 y	2 x	2 y	3 x	3 y	4 x	4 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

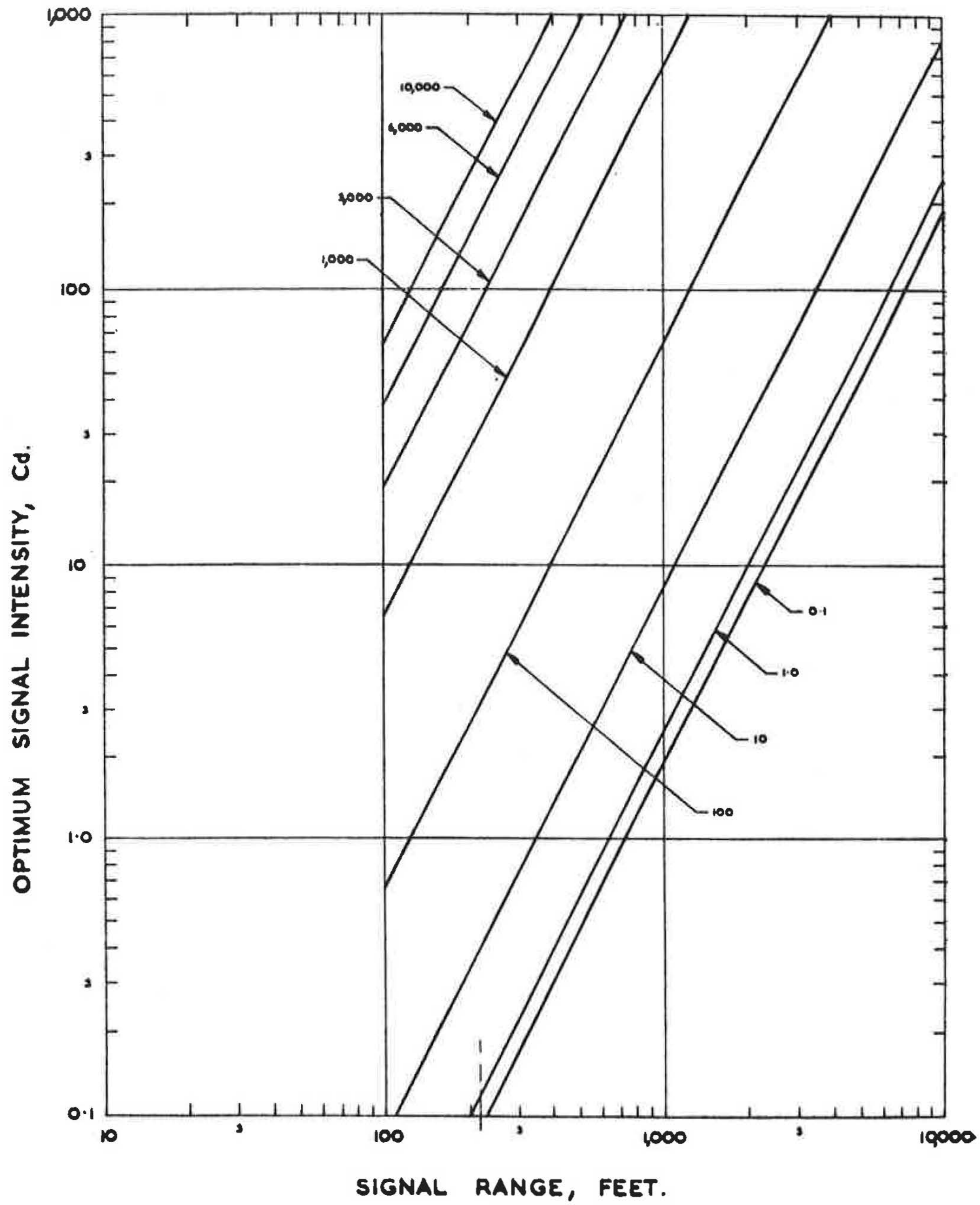

FIGURE 1 Nomogram showing optimum intensity for red road traffic signal as function of maximum signalling range for various background luminances in foot lamberts (*6*).

TABLE 2 PEAK DAYTIME INTENSITY REQUIREMENTS

	PEAK INTENSITY REQUIREMENT (cd) (MAINTAINED; NO BACKPLATE)		
SIGNAL SIZE	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/m^2 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

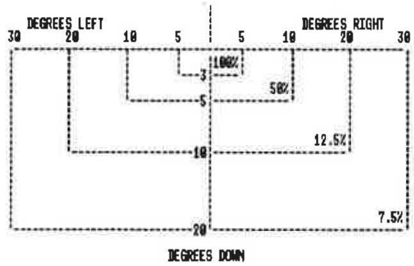

FIGURE 2 Optimum intensity distribution (percent of peak intensity) (*13*).

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/m^2), 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/m^2).

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	Vertical (degrees)		
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	Vertical (degrees)		
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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