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Standard Guide to Properties of High Visibility Materials Used to Improve Individual Safety[1]

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INTRODUCTION

For many years the problem of pedestrian–motor vehicle collisions has been a major one in the United States and the rest of the world. In the U.S., in the last three years for which data are available (1988–1990), there have been on the average about 8200 pedestrian fatalities per year, of which about 54 % occurred at night (**1**).[2] In addition, over 100 000 pedestrians were injured by motor vehicles each year (**2**).

Lack of adequate visibility and conspicuity of pedestrians at night and during the day is considered to play a direct role in many of these accidents. An investigation of pedestrian accidents lists the following six driver and pedestrian actions necessary for safe travel: search, detection, evaluation, decision, human action, and vehicle action (**3**).

Research shows that pedestrians typically overestimate their visibility (**4**). Since the average pedestrian is not likely to be able to determine means for establishing adequate visibility, guidelines are needed to improve visibility and conspicuity of pedestrians. Guidelines and, in fact, standards (**5, 6**) have been provided for other road users (for example, trucks, passenger cars, motorcycles, and bicycles) in an attempt to meet visibility needs, but not for pedestrians. This guide provides general principles for the enhancement of pedestrian visibility both at night and during the day. These principles also generally apply to anyone else exposed to motor vehicles, including construction workers, airport workers, bicyclists, and motorcyclists.

1. Scope

1.1 This guide covers the physical principles and variables involved in the performance and selection of high visibility materials for individual safety.

1.2 It is the purpose of this guide to examine the principles on which future standards relating to individual safety may be used. However, this guide does not set minimum standards for the properties of high visibility materials.

1.3 In reviewing the principles contained in this guide, it must be remembered that there are numerous factors adversely affecting visibility and safety (for example, rain, snow, road grime, alcohol, advanced age, drugs, fatigue, inattention, headlamp misalignment or breakage) that must be taken into account when dealing with actual safety requirements.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 1535 Practice for Specifying Color by the Munsell System[3]

D 2244 Test Method for Calculation of Color Differences from Instrumentally Measured Color Coordinates[3]

E 284 Terminology of Appearance[3]

E 308 Practice for Computing the Colors of Objects by Using the CIE System[3]

E 808 Practice for Describing Retroreflection[3]

E 809 Practice for Measuring Photometric Characteristics of Retroreflectors[3]

2.2 *Other Standards:*

[1] This guide is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.08 on High Visibility Materials for Individual Safety.

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[3] *Annual Book of ASTM Standards*, Vol 06.01.

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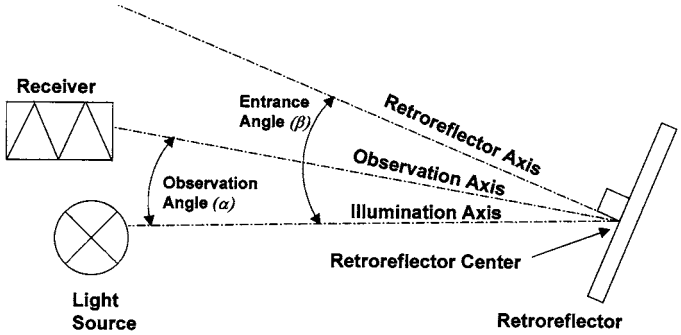

NOTE 1—This figure illustrates the test geometry frequently employed when entrance angle and observation angle only are specified. The illumination axis, observation axis, and retroreflector axis are in the same plane. Although the entrance angle β is, by definition, always positive (see Practice E 808), specifying a negative value (such as –4°) for β in this geometry is intended to correspond to locating the observation axis and retroreflector axis on opposite sides of the illumination axis. The entrance angle as illustrated in this figure would then correspond to positive values of β. The observation angle is always positive. See also Fig. 3 and Fig. 4.

FIG. 1 Retroreflection Geometry

CIE S002 Colorimetric Observers[4]

SAE J579c Sealed Beam Headlamp Units for Motor Vehicles[5]

3. Terminology

3.1 *Definitions*—Terms and definitions in Terminology E 284 and Practice E 808 are applicable to this guide.

3.1.1 *brightness*, *n*—attribute of a visual perception according to which an area appears to emit more or less light.

3.1.2 *conspicuity*, *n*—the characteristics of an object that determine the likelihood that it will come to the attention of an observer.

3.1.3 *divergence angle*, *n*—use the preferred term, **observation angle.**

3.1.4 *entrance angle,* β, *n*— *in retroreflection*, the angle between the illumination axis and the retroreflector axis.

3.1.4.1 *Discussion*—This is the angle formed by a light ray striking a surface and a line perpendicular to the surface at the same point (Fig. 1). The surface is commonly depicted as a flat planar surface such as a sign face, but it applies as well to curved or irregular surfaces as when used on clothing. The entrance angle is sometimes referred to as the "incidence angle." It is desirable for retroreflective materials to remain bright through as wide a range of entrance angles as possible. This feature is especially important for retroreflective treatments worn by pedestrians because of the many positions and angles at which the pedestrian and apparel may be viewed by drivers.

3.1.5 *goniometer*, *n*—an instrument for measuring or setting angles.

3.1.6 *observation angle,* α, *n*—the angle between the illumination axis and the observation axis.

3.1.6.1 *Discussion*—This is the angle between a line formed by a light beam striking a surface (such as a sign face) and the line back to the observer's eye from the point (Fig. 1). By knowing how far one is from the light source and the surface, one can compute the observation angle. Either the sine or tangent function can be used to calculate it. This angle must be quite small (2° or less, preferably 0.5° or less) for presently available retroreflective materials to function effectively. The observation angle is sometimes referred to as the "divergence angle." The observation angle is important because retroreflected light is returned as a narrow cone with the inner part of the cone (smaller observation angles) being most intense (Fig. 2).

3.1.7 *orientation angle,* ω_s, *n*—the angle in a plane perpendicular to the retroreflector axis from the entrance half-plane to the datum axis, measured counter-clockwise from the viewpoint of the source.

3.1.8 *pedestrian*, *n*—any person on foot (standing or moving) who is located on a highway or street.

3.1.9 *presentation angle,* γ, *n*—the dihedral angle from the entrance half-plane to the observation half-plane, measured counter-clockwise from the viewpoint of the source.

3.1.9.1 *Discussion*—A full discussion of presentation angle is complicated and will not be given here. It is of importance in photometric measurement where either coplanar or perpendicular presentation geometries are used. The actual situation encountered on the roadway is usually intermediate.

3.1.9.2 *Discussion*—In laboratory measurements where components of the entrance angle are used in setting the actual laboratory goniometer settings, the presentation angle is mathematically related to these components. See Practice E 808 and Fig. 3 and Fig. 4.

3.1.10 *refraction*, *n*—change in the direction of propagation of radiation determined by change in the velocity of propagation in passing from one medium to another.

3.1.10.1 *Discussion*—The change in direction of propagation follows Snell's law (Figs. 5 and 6). When the medium containing the incident beam has the higher refractive index (Fig. 6), a critical angle can be reached beyond which light cannot be transmitted but is reflected. For angles greater than the critical angle, total internal reflection occurs. Most prismatic retroreflectors depend on this principle in order to function.

3.1.11 *rotation angle,* ϵ, *n*—the angle in a plane perpendicular to the retroreflector axis from the observation half-plane to the datum axis, measured counter-clockwise from a viewpoint on the retroreflector axis.

3.1.11.1 *Discussion*—The rotation angle is measured from a datum mark on the retroreflector and is positive in the

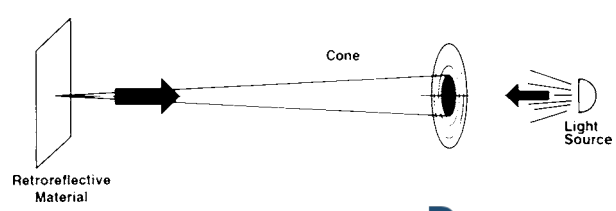

FIG. 2 Cone of Retroreflected Light

[4] Available from the USNC-CIE Publications Office, c/o TLA Lighting Consultants, Inc., 72 Loring Avenue, Salem, MA 01979.

[5] Available from the Society of Automotive Engineers, 400 Commonwealth Avenue, Warrendale, PA 15096.

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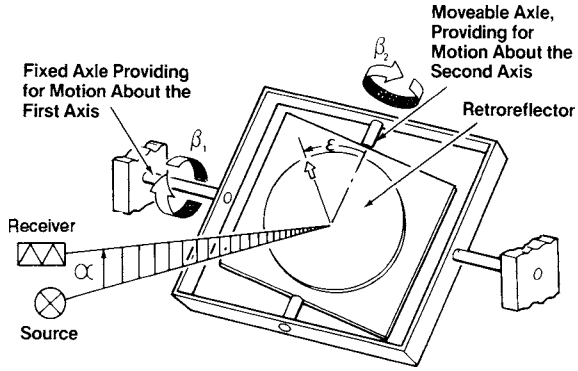

FIG. 3 Measurement Geometry (ASTM-CIE System)

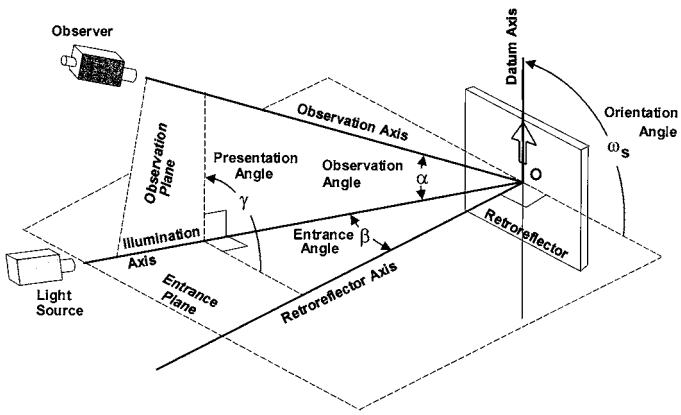

FIG. 4 Measurement Geometry (Intrinsic System)

counterclockwise direction (clockwise rotation of the retroreflector, Fig. 3 and Fig. 4). Very large rotation effects can occur without the retroreflector itself rotating by virtue of changes in distance and geometry between the observer and target. Prismatic or cube-corner retroreflective surfaces typically vary somewhat in brightness when rotated. Spherical-lens sheeting has only a minimal rotational response. On the roadway, rotational effects are usually less significant than changes in observation or entrance angles.

3.1.12 *Snell's law*, *n*—the product of the sine of the angle of refraction by the refractive index of the refracting medium is equal to the product of the sine of the angle of incidence by the index of refraction of the medium containing the incident beam.

3.1.13 *visibility*, *n*—the properties and behavior of light waves and objects interacting in the environment to produce light signals capable of evoking visual sensation.

3.1.14 *visual perception*, *n*—the visual experience resulting from stimulation of the retina and associated neural systems.

4. Summary of Guide

4.1 This guide reviews the factors affecting and gives examples of high visibility materials for individual safety.

4.2 This guide emphasizes passive high visibility materials, but certain active sources important to the functioning of passive materials are also covered.

5. Significance and Use

5.1 The principles elucidated in this guide should be carefully considered in the preparation of standards for the development and use of high visibility materials. The guide does not, however, contain specific test methods or recommended visibility levels.

6. Vision and Visibility

6.1 *General*—The terms visual perception and visibility are defined in 3.1.14 and 3.1.13, respectively. They imply a distinction between the observer and the observed object in the environment. To the observer, vision and visual perception are the important elements. Visibility, on the other hand, is a property of the object (which can be a pedestrian or other road object), its background and illumination, and the transmission of light to the eye of the observer. Thus, to improve the entire system, one might try to improve human vision or teach people to perceive and interpret signals better. Another approach would be to improve the visibility of objects by making them more conspicuous and more recognizable.

6.2 *Vision*:

6.2.1 The human eye responds to radiant energy roughly between the wavelengths of 380 and 780 nm. There are two types of photoreceptor cells in the eye, cones, and rods. Cones are concentrated in the center of the retina (light sensitive tissue) called the fovea and are responsible for color perception and the ability to distinguish fine details. Cones operate best at higher light levels (daytime, bright lights) producing what is termed "photopic" vision. Rods predominate in the retinal periphery and are quite sensitive to motion and to visual stimuli at low light levels under "scotopic" vision conditions (night, dark rooms). Intermediate to the photopic and scotopic states is the mesopic range, where both the rods and the cones are operative. Night driving, in general, produces the mesopic visual condition. The eye is remarkably sensitive; the minimum signal that can be reliably detected is said to consist of no more than about five photons for rods (**6**).

6.2.2 Central vision covers a solid angle of about 5° in the center of the fovea and is needed for such functions as acuity, judgment of speed, and color vision. Peripheral vision is the remainder, extending out to cover the forward 180° field of view. Although much less sensitive to color due to the presence of very few cones, the eye's periphery responds to bright, flashing, and moving lights. This enables a person to monitor much of the environment and selectively switch central vision to the more prominent visual phenomena as they occur.

6.2.3 The slightly different image seen by each eye and integrated by the mind give rise to stereopsis, the ability to see in three dimensions. For driving, however, this is not as important a visual cue of distance as are perspective and overlay cues which impart information by position on the terrain, size, and shadowing effects.

6.2.4 Color vision is mediated by three types of cones, responsive to short, medium, and long wavelengths in the 380 to 780 nm visible spectrum, with response functions that are extensively overlapped. The overall response of the visual system to incoming power is given by the spectral luminous efficiency function $V(\lambda)$, a bell-shaped curve peaking at about

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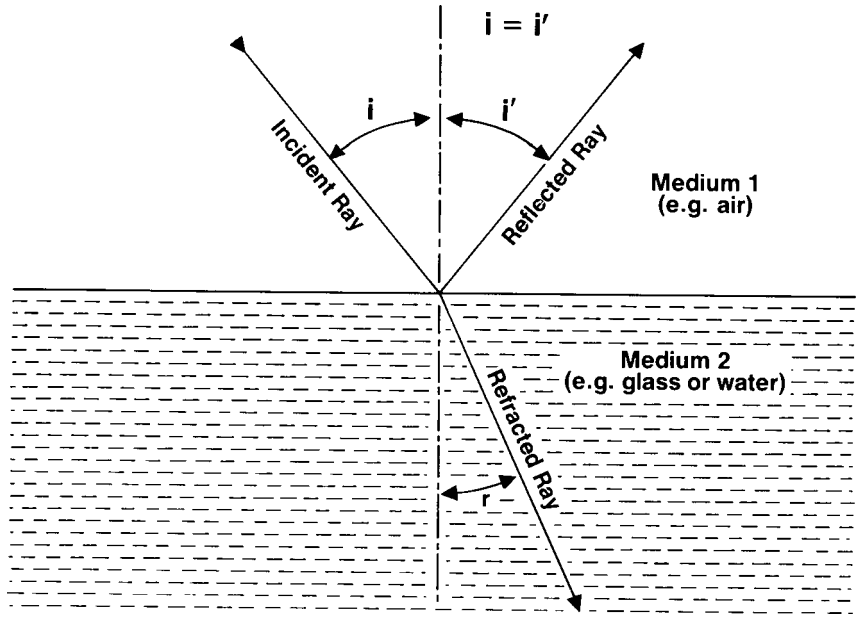

FIG. 5 Refraction—From Lower to Higher Refractive Index

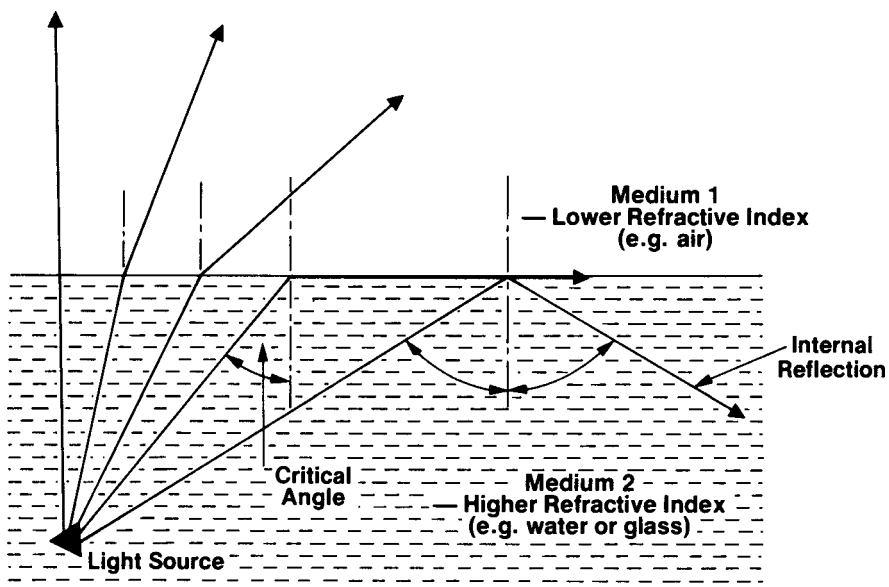

FIG. 6 Refraction—From Higher to Lower Refractive Index

555 nm for photopic (cone) vision and dropping to zero at the ends of the visible region. This function and the sets of color-matching functions characterizing the color-vision properties of the average human eye have been adopted by the CIE (Commission Internationale de l'Eclairage, International Commission on Illumination) to define standard observers for the foveal (2° field) and extrafoveal (10° field) regions of the retina (CIE S002 and Practice E 308). The sciences of colorimetry and photometry are based on these functions. They apply reasonably well to real observers except when color-vision deficiencies result from one or more types of cone being missing or inoperative.

6.2.5 An important property of the eye is its ability to judge the perceived brightness (see 3.1.1) of an object, light source, or other color stimulus. Although such judgments are subjective, they play an important role in determining conspicuity. In the CIE system described above, the psychophysical (objective, measured) correlate of brightness is luminance, Y, which is obtained by multiplying the spectral power of the stimulus, wavelength by wavelength, by the spectral luminous efficiency function $V(\lambda)$ and summing the products over the visible wavelength range, 380–780 nm. It is often assumed that luminance and perceived brightness correlate perfectly (for example, this is assumed in the Munsell system for luminance and Munsell value; see Practice D 1535). However, this assumption is not valid when comparing different colored stimuli. In that case, a correction factor known as the brightness to luminance (B/L) ratio, which is a function of hue and saturation, must be applied. Determining the B/L ratio is difficult, involving visual experiments in which one finds out

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different colors must be adjusted to match in brightness (heterochromatic brightness matching). Consequently, many sets of B/L ratios are reported in the literature. Those that appear to be most useful for applications involving retroreflective materials are found in ref. (**7**).

6.2.6 The eye is remarkably adaptive to a wide range of illumination levels, approximately 10^{-6} to 10^{6} cd/m^2 in luminance. No single element of the eye has such a wide dynamic operating range; it is achieved by a combination of compression, adaptation, and specialization mechanisms (**8**). One result is that, for the mesopic region (near 1 cd/m^2) associated with night driving, the subjective sensation of brightness increases by only about a factor of four for each tenfold increase in the measured luminance (**9**). Very high luminances can cause temporary or permanent loss of vision. Glaring light can produce discomfort glare which is uncomfortable to look at but does not necessarily impair vision. Glaring light can also produce disability glare which causes at least a temporary vision loss.

6.2.7 As one ages, the eye loses some of its visual acuity and sensitivity, possibly because of reduction in blood supply to the retina, reduction in maximum opening of the iris, and yellowing of the lens. As a result visual performance declines from its peak in the teens by about a factor of three by age 80 (**10**). Recovery from glare takes longer with increasing age. Older persons may perform as well in the daytime under high ambient lighting conditions but experience low acuity and contrast sensitivity at night.

6.3 *Visibility and Visual Perception:* (**11**)

6.3.1 Table 1 shows, for the highway setting, the relation of successive aspects of visibility to corresponding responses of the observer on perception.

6.3.2 The four elements of visual perception shown in Table 1 are distinct sequential phases that correspond to visibility information from the roadway and usually follow in the order shown for an unalerted driver, that is, a driver who is not expecting to encounter a pedestrian or other hazard. Thus, an object may become capable of being detected as a driver approaches but is not detected immediately. After detection, the driver needs to pay attention to the object and may or may not recognize what it is. Finally, if the object appears capable of intersecting the vehicle's path, closing rate, deceleration, headway, lateral offset, and the like, are determined by localization. In considering ways to improve visibility, all of these perceptual functions should be taken into account.

6.3.3 A system that provides only marginal detectability for properly oriented and alerted drivers, for example, should not be considered adequate since such a system fails to address the real visibility needs on the roadway. In a similar manner, conspicuity (that is, attention-getting targets quickly detected at significant distances) may not be enough if important succeeding dimensions such as recognizability and localizability are lacking.

TABLE 1 Relations of Object Visibility to Perceptual Response

Visibility of Pedestrian or Road Object	Perceptual Response
Detectability	Detection (distance dependent)
Conspicuity (noticeability)	Fixation-attention (time dependent)
Recognition	Recognition (identifying relationships)
Localizability	Localization (space-time relationships)

6.3.4 After the visual perception process has taken place, further time is needed by a driver for decision, motor response of hand or foot, and vehicle response (for example, braking action). The length of time for the visual perception-decision-motor-reaction-vehicle response sequence is variable, each element being influenced by several factors. Some of these factors are fatigue, distraction, alcohol, drugs, age, past driving experience, weather conditions, road conditions, and vehicle handling properties. As a result of this variability, one cannot assign strict times and distances for stopping or maneuvering at various speeds.

6.3.5 To cope with the variability of visual perception-decision-motor-reaction-vehicle response, traffic engineers use a measure termed "stopping sight distance" (SSD). SSD assumes a 2.5 s total perception/reaction time followed by vehicle deceleration which varies with the coefficient of friction for the roadway (that is, dry or wet conditions) and roadway grade. For 88 km/h (55 mph) on a straight roadway under wet conditions, this translates to a total of 170 m. SSD applies when the situation is one that is understood by the driver as, for example, when he knows he must stop to avoid a pedestrian in front of him.

6.3.6 Another measure that has been proposed is termed" decision sight distance" (DSD). DSD might apply if the driver is uncertain whether an object really is a pedestrian, where the object is with respect to the traveled lane, and what movements might occur. Based on longer reaction times than those normally associated with SSD, the average DSD for 88 km/h (55 mph) is about 300 m. See Table 2 for recommended decision sight distances (**12**).

6.3.7 Of the two, DSD is the more conservative, covers more of the dangerous road situations, and is the preferred distance when considering high visibility materials for improved conspicuity. It would be desirable, for example, to wear high visibility markings that are conspicuous and even recognizable at 300 m or more on roadways where speeds are 88 km/h and higher.

7. Properties of High Visibility Materials

7.1 Visibility involves light waves interacting with objects in the environment. Several aspects of this process are reviewed in 7.2-7.4.

7.2 *Primary and Secondary Light Sources*—As defined in Terminology E 284, *primary light sources* generate and emit light, that is, they are self-luminous. The sun, vehicle headlamps and taillights, fixed roadway lighting, and flashlights are some examples. Primary light sources are usually seen in the *illuminant mode*. Objects that are not self-luminous but reflect light are called *secondary light sources*. They are usually seen in the *object mode*. All surfaces reflect light to some extent. Those which are designed to reflect in a very efficient way have been termed "high visibility materials."

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