Effect of Luminaire Arrangement on Object Visibility

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The visibility of small objects is affected more by the contrast between the outline of the object and the background than by the adaptation level produced by the pavement luminance. Because the object luminance is likely to be produced by a different luminaire than most pavement luminances, the contrast can be controlled by the lighting system designer. Both the pavement and the object have distinct directional light reflectance properties; hence, the luminaire arrangement is one of the major factors used in determining the direction from which light reaches both the object and its background. The substantial changes in visibility that occur as the result of the choices made in luminaire arrangement and light distribution are explored. These explorations are made by studying the visibility of a small standard target placed on a grid overlay on the pavement. The resulting Small Target Visibility can be calculated and summarized to serve as a criterion for the quality of the roadway lighting system.

There is no question that some light is required to drive a vehicle safely. The light may come from the sun, the moon, vehicle headlights, or fixed lighting, but there must be some light to make our human visual system effective. The questions are, "how much light?" and "how does one determine the quality of the lighting?" One answer is, "enough to make things visible."

A measure of the quantity of light reaching the road surface or reflected from it has been used to determine the amount of light required from a fixed lighting system. A candlepower/angle specification of headlight output distribution for vehicle headlights has also been used.

The use of a visibility measure is gaining acceptance by both the fixed roadway lighting community and by the headlighting group. One such measure, loosely called "Small Target Visibility" (STV), will probably be used to specify the quality of fixed roadway lighting in the next edition of ANSI RP-8 (*1*). In vehicle headlighting the tendency is to use several targets, such as a stylized pedestrian, a small object, and a lane line. Such objects are used in the Chess Headlighting Evaluation Program (*2*).

It is necessary for the designer of a lighting system or luminaire to understand the interaction of the various factors that improve or degrade such a surrogate measure. The purpose of this paper is to discuss those factors with regard to the measure called STV.

SMALL TARGET VISIBILITY

STV, as defined by the Roadway Lighting Committee (RLC) of the Illuminating Engineering Society (IES), is the measurement or calculation of the visibility level of an 18-cm (7-in) square, flat target located on a flat, level roadway 273 ft from an observer that is 1.45 m above the pavement and on a line parallel to the center line of the roadway. The target surface has a diffuse reflectance of 20 percent and is located at 90° to both the observer's line of sight and the roadway surface. The visibility level (VL) is the amount the target is above threshold for a standard observer (*3*). A lighting installation is given an STV rating by evaluating the visibility of such a target located at many points in the installation. It is common to use the 20th percentile as the rating number.

STV, like other measures such as horizontal lux, pavement luminance, vertical lux, hemispherical lux, or semicylindrical lux, is measured or calculated at a large number of grid points over the roadway surface. STV has been correlated to driver performance by Gallagher (*4*), and top vehicular accidents by Janoff (*5*). It is a surrogate measure, however, and does not necessarily correlate with all of the different visual tasks a driver encounters. It is not the purpose of this paper to discuss the merits or deficiencies of STV, but to discuss the ways a designer can improve the STV rating of a lighting system. The factors that determine the VL of a small target are as follows:

- The adaptation level of the human visual system: Adaptation determines the sensitivity of the visual system to both contrast and glare.
- The contrast between the target and its background: In the arrangement previously discussed, the background behind the small target is always the luminance of the roadway pavement surface. Both the luminance of the target and the roadway surface can be calculated.
- The size of the small target: In the definition previously mentioned, size is constant.
- Transient adaptation, the result of the adaptation change from the point last fixated by the moving eye: This is neglected in current calculations because the research defining it is still ambiguous.

To improve or degrade STV, as previously defined, it is necessary to consider only three factors—adaptation level, contrast, and glare—because the target size is constant.

Adaptation Level

Adaptation level is roughly defined by the horizontal lux over footcandle (fc) level. The average level on the roadway from the observer to 500 ft ahead may be as much as 5,000 fc from daylight; a fixed lighting system provides from 0.5 to 4.0 fc

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and a headlighting system from 0.001 to 0.1 fc. A more accurate method of defining adaptation level is by measuring the luminance over a given angular field. A circular field of 1.5°, centered on the point of visual fixation, is often used to determine adaptation level in visibility calculations.

The adaptation level produced by a fixed lighting system (streetlights) can be changed by several means. The most common is to change the lamp size or the number of units per mile (spacing). If the light output is varied by means of a dimming system with no change in the arrangement of the lighting system, then STV will increase as light level increases. The relationship for a typical street lighting system is shown in Figure 1 (the contrast is constant at 0.5 and the Lv is constant at 0.2). Doubling the light level from 1 to 2 cd/m^2 increases the target VL by about 20 percent, provided the luminaire arrangement and luminaire distribution are unchanged.

Contrast

Contrast is the most powerful factor in determining the visibility of a small target. Contrast is usually defined as the luminance of the target minus the luminance of the background with the quantity divided by the luminance of the background.

$$\text{Contrast} = \frac{L\ (\text{target}) - L\ (\text{background})}{L\ (\text{background})}$$

Contrast may be either positive or negative depending on whether the luminance of the target is greater than or less than the luminance of the background. Less obvious is that negative contrast can vary only between 0 and -1 whereas positive contrast can vary from 0 to infinity. Figure 2 shows the relationship between STV and contrast with all other factors held constant (the adaptation level is constant at 1 cd/m^2 and the Lv is constant at 0.2). Doubling the contrast doubles the target VL.

The human visual system easily detects and recognizes object shape under either positive or negative contrast situations. Negative contrast is often called "silhouette" vision. Black printing on white paper or white printing on black paper can be read with no particular problems.

Glare

The eye is not hollow and the material between the lens and the retina is not perfectly clear. Light that enters the eye is scattered by imperfections in the aqueous humor and acts as a luminous veil that reduces the contrast to the receptors on the retina. The severity of this scattering normally increases with the age of the individual. The effect of veiling luminance (Lv) is a function of the amount of light entering the eye and the angular location relative to the line of sight. The relationship between STV and Lv, with other factors constant, is shown in Figure 3 (the contrast is constant at 0.5 and the adaptation level is constant at 1 cd/m^2). It is easily seen that the effect is relatively mild with an adaptation level of 1 cd/m^2.

Glare from oncoming headlights is particularly severe if the adaptation level is very low. The angle between the driver's line of sight and the oncoming vehicle is small and the amount of light entering the eye from the oncoming headlights may be high. In daylight, or even under a fixed lighting system, the adaptation level may be sufficiently high so that the same

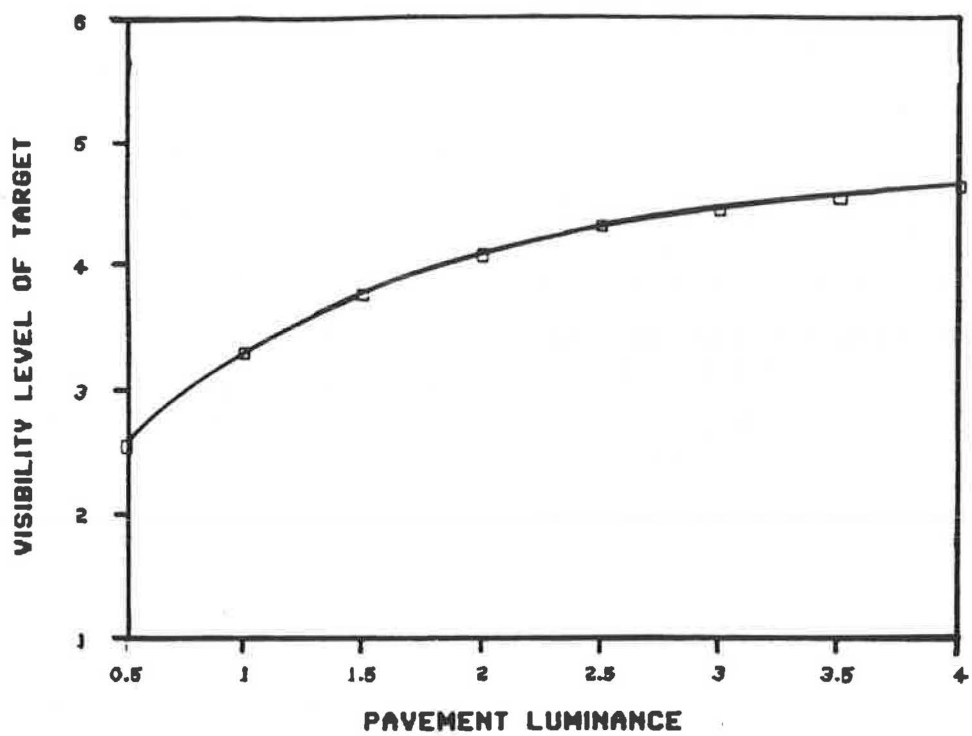

FIGURE 1 Relationship of target visibility level to adaptation: pavement luminance in candles/m^2.

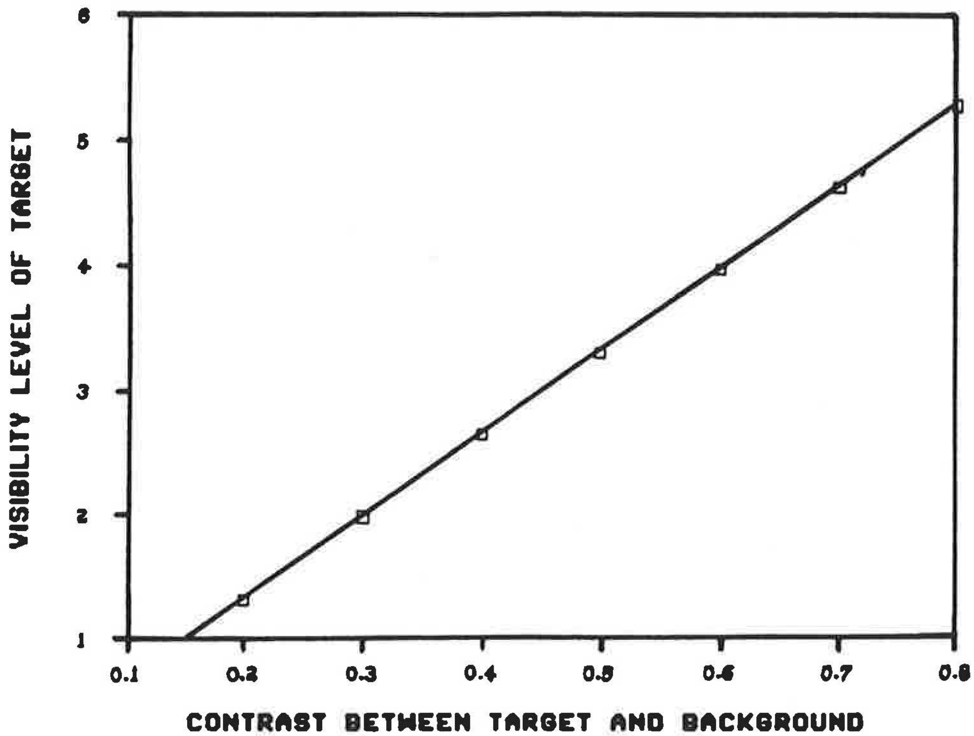

FIGURE 2 Relationship of target visibility level to contrast between target and its background.

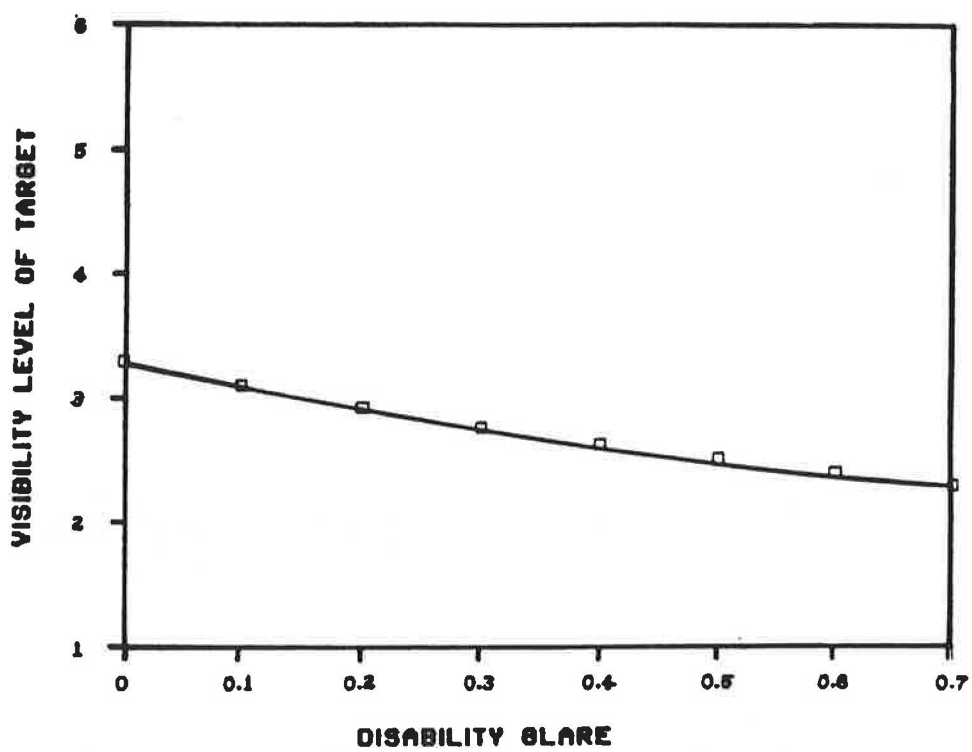

FIGURE 3 Relationship of target visibility level to veiling luminance (disability glare).

quantity of Lv from oncoming headlights has little effect on STV.

LUMINAIRE ARRANGEMENT AND CONTRAST

Contrast between the object (target) and the background may be altered by changing the reflectance of each. The highway designer has some control over certain reflectances. He specifies the materials used for the pavement, lane markers, signs, and the types of grass or other material used adjacent to the pavement. There is literally no such thing as a perfectly diffuse reflectance material. The reflectance of all practical materials is a function of the angle at which light strikes the material versus the angle of the line of sight of the observer. This is called the bidirectional reflectance-distribution function (BRDF). In the roadway situation, the driver is always located in a vehicle with a small range of height above the roadway, and his line of sight is nearly always directed ahead and slightly down as he looks to determine the run of the road ahead and if it is clear of obstacles and other traffic.

For fixed lighting installations, the lighting designer has a great deal of control over the direction from which light strikes the object (target) and the pavement. As a result, he can exert considerable control over contrast and the resulting small target visibility. The designer or specifier of the luminaire distribution has some control over the amount of light and the angles at which it is emitted in the case both of fixed lighting equipment and headlighting equipment.

The first important concept to understand is that STV may be increased using one technique to increase the light level and that it may be decreased if an alternate technique is used.

Bidirectional Lighting Systems

The vast majority of all fixed lighting luminaires in service today have a bidirectionally symmetric distribution: two equal beams, one pointed upstream towards traffic and one pointed downstream. Consider a situation in which there is a single fixed luminaire distance of 273 ft. If two targets and an observer are located (see Figure 4), one target is seen by negative contrast, because no light from the fixed luminaire reaches the face of the target, and the other target is seen by positive contrast, because the luminaire is not very effective in producing pavement luminance in this direction due to the BDRF of the pavement surface. There must be some contrast reversal point from negative to positive as the target is moved from one location to another. At and near the point of contrast reversal, the visibility of the target drops below threshold and it is not visible to a standard observer. The location of this contrast reversal point (and disappearance of the flat target) is slightly beyond a point directly under the luminaire. The contrast reversal area below a luminaire is normally narrow for a three-dimensional object and often not recognized by a casual observer.

If two luminaires (with twin beams of equal magnitude) and four targets are used as shown in Figure 5, it is found that there must also be a reversal point between luminaires to regain the negative contrast condition that exists when the target is close to the next luminaire. This area of contrast reversal may be sharp or gradual depending on the relationship between the spacing-to-mounting height ratio and the luminaire distribution. Small three-dimensional objects often completely disappear in this area even though there may be considerable pavement luminance present. In the event the vehicle is using a high beam headlight (or a misaimed low beam headlight), there is often sufficient change in the target luminance to shift or broaden the location of this contrast reversal area of a fixed lighting installation.

The relationship between the spacing-to-mounting height ratio and the luminaire distribution is critical in determining the location and sharpness of the contrast reversal area between luminaires. Figure 6 shows that excessive overlap between the upstream and downstream beams of a conventional luminaire may result in nearly equal luminances of the target face and the pavement over a broad area. In practice, this means that the decision to increase the amount of pavement luminance by reducing the spacing is likely to cause such a severe reduction in contrast that the overall STV will be reduced in spite of a rise in adaptation level.

The second concept to note is that the relationship between luminaire spacing and vertical light output must be coordinated. In order to optimize STV, it is essential to choose the combination of luminaire locations and light distribution that creates short abrupt areas of contrast reversal. Figure 7 uses the same luminaire spacing but, by selecting a luminaire with a lower angle of emitted light, the excessive overlap is eliminated.

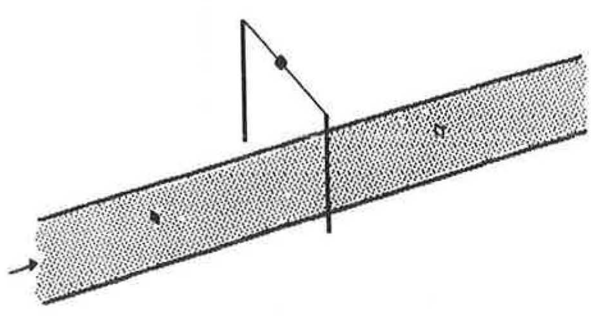

FIGURE 4 With a single luminaire and two targets, one target will have negative contrast and the other will have positive contrast.

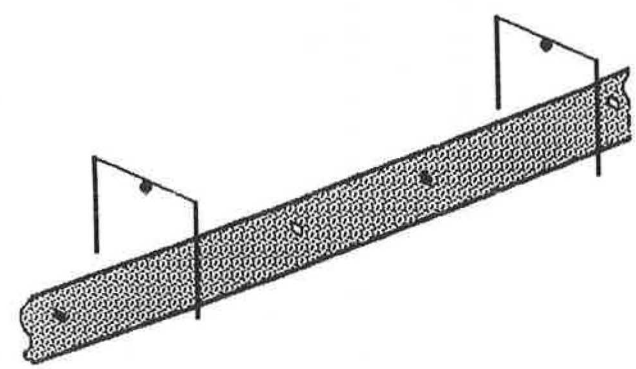

FIGURE 5 With multiple luminaires and multiple targets, contrasts will reverse below each luminaire and between luminaires.

Figure 8 indicates the probable location of contrast reversal with center-mounted luminaires and an opposite arrangement of luminaires. The lines of contrast reversal are short and perpendicular to the roadway centerline. Figure 9 indicates that the pattern of contrast reversal can become quite complex for staggered and one-side arrangements. In such arrangements, the below threshold area adjacent to the long contrast reversal lines may be quite large compared to the total roadway area. The third concept is to choose luminaire locations that produce short, abrupt lines of contrast reversal when using conventional twin beam streetlighting luminaires.

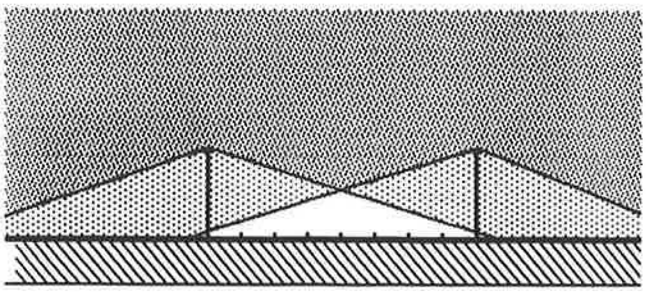

FIGURE 6 Luminaires with high vertical angle of maximum candlepower and short spacing produce excessive overlap that reduces contrast.

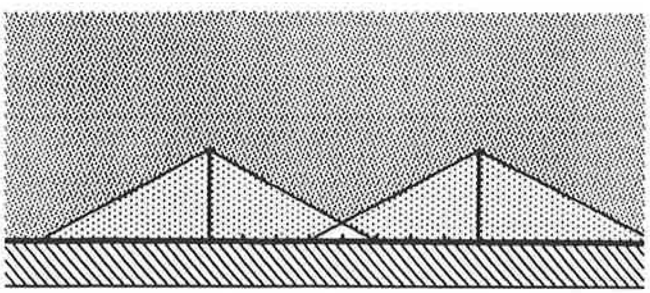

FIGURE 7 Luminaires with lower vertical angle of maximum candlepower reduce overlap and increase target to background contrast.

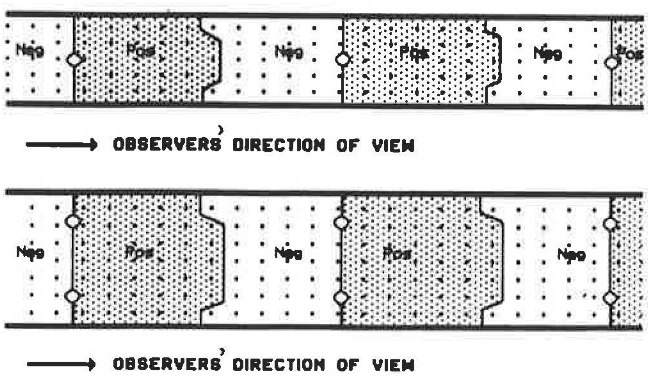

FIGURE 8 Probable lines of contrast reversal with twin beam luminaires arranged to minimize length of such contrast reversal lines.

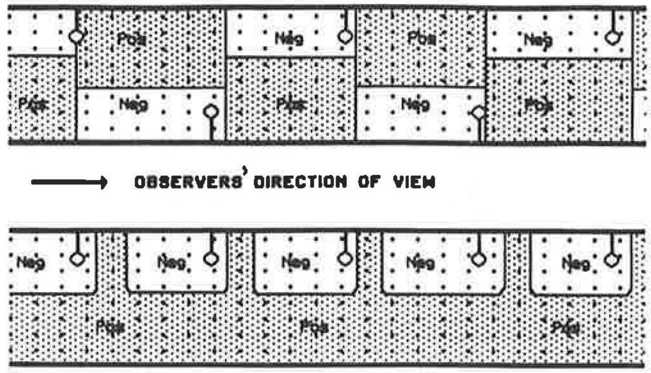

FIGURE 9 Probable lines of contrast reversal of similar luminaires with staggered and one-side arrangements.

Unidirectional Lighting Systems

Automotive headlighting systems are close to the ultimate in terms of a unidirectional lighting system that produces a very high level of small target visibility. The BDRF (directional reflectance) characteristics of the horizontal pavement produce a low background luminance, whereas the high beam candlepower striking the vertical surface of the target produces a high level of target luminance and results in high positive contrast and good STV. There is no contrast reversal under normal situations. The chief problem is the glare from the headlights of oncoming cars on roadways carrying traffic in two directions.

It is possible to design and build luminaires for fixed lighting systems which use the same concepts. If the effects of the automotive headlighting system are disregarded, then the most energy-efficient fixed lighting system would be one that directs the light toward the stream of traffic (upstream lighting) (see Figure 10). Virtually all detection and recognition would be by negative contrast and the BDRF characteristics of the pavement make possible the creation of a high adaptation level with a low level of watts/ft^2 of energy. Glare from the fixed lighting units is not an insurmountable problem and would be far less than the glare from the headlights of oncoming cars. The major problem is the interaction of such a lighting system with the vehicle headlamps that are trying to produce visibility in exactly the opposite manner.

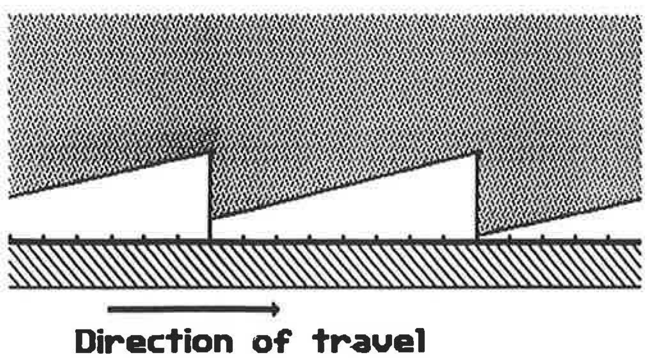

FIGURE 10 Unidirectional luminaire distribution (single beam) directed upstream produces excellent pavement luminance and negative target to background contrast.

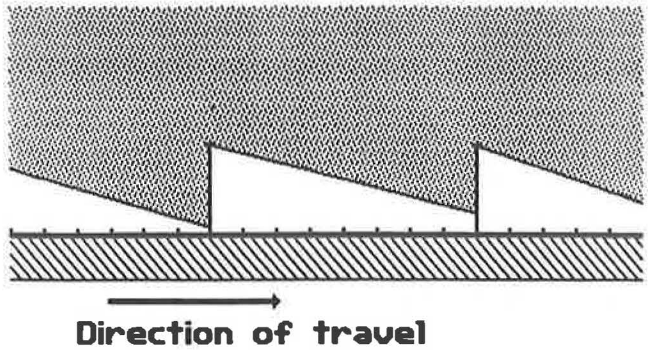

FIGURE 11 Unidirectional luminaire distribution (single beam) directed downstream produces lower pavement luminance and positive target to background contrast.

It is also feasible to produce luminaires for a fixed lighting system that direct all of their light in the same direction as the traffic stream (see Figure 11). Such luminaires would be more efficient in producing pavement luminance (adaptation level) than would vehicle headlamps, the STV would all be positive, and the fixed lighting system and the headlights would be working together to produce the same effect. It seems probable that such luminaires will be introduced for one-way streets and roadways in the future.

Off-Roadway Locations for Luminaires

For many years the conventional twin-beam roadway luminaire has been designed for mounting over the paved area of the road. High mast lighting uses luminaire locations away from the pavement as do some specialized low-mounted luminaires designed to be mounted some distance from the pavement. Such luminaires are less efficient in terms of producing pavement luminance than the conventional twin-beam luminaire mounted over the pavement that directs 50 percent of its light in a more favorable direction. Effective small target visibility, however, is easily generated by using the difference in BDRF characteristics of the target and the pavement to create contrast, which is the most powerful factor in producing visibility level. Computer explorations of existing luminaire distributions for off-roadway luminaires indicate the positive STV contrast that can be generated, without contrast reversal, effectively with such distributions. This can almost certainly be applied to high mast lighting techniques and further increase in the use of these luminaires in providing lighting with high levels of positive STV.

Zero Reflectance Objects

It should be kept in mind that small target visibility, as defined by the RLC, uses a target with a 20 percent reflectance. Positive contrast cannot be achieved with objects that have zero reflectance. Zero and near-zero reflectance objects can be detected and recognized only in terms of being darker than their background. Pedestrians wearing black raincoats or all-dark clothing are very difficult to detect with only vehicle headlights and, thus, the National Safety Council advises pedestrians walking on or across roadways at night to wear light-colored clothing.

It should be remembered that any principles discussed in this paper that involve contrast reversal do not apply to zero reflectance objects. It is not the purpose of this paper to discuss the extent or probability of zero or near-zero reflectance objects being involved in the cause of automobile accidents.

SUMMARY AND CONCLUSIONS

The objective of both vehicular headlighting and fixed roadway lighting is to reveal the run of the road ahead and the presence of objects and traffic that may result in an accident. It is important to evaluate the interaction between headlights and fixed lighting in revealing to the driver important visual tasks. Surrogate measures of lighting effectiveness that do not incorporate the principles involved in creating object visibility make it impossible to evaluate this interaction. Small target visibility is a surrogate measure that uses the known principles of visibility modeling. In order to generate high levels of STV, some traditional concepts of fixed lighting design must be revised. In particular, it appears that the following concepts must be incorporated into the design of fixed lighting systems:

- Luminaire placement must be selected to minimize contrast reversal areas.
- Luminaire light distributions must be flexible and available in terms of a variable vertical angle of maximum candlepower.
- Unidirectional luminaire distributions should be considered for one-way traffic areas.
- Consideration should be given to locating luminaires away from the roadway pavement and projecting the light in distributions that optimize object visibility.

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