

Should vision influence roadway lighting design?

by Ian Lewin

Nighttime visibility is a critical issue to users of our highways and to those involved in street lighting design. Roadway accidents occur at a much greater rate during night hours than during the day. While there are many reasons for this, the major cause is believed to be reduced visibility due to low light levels. Economics and technical obstacles prevent lighting professionals from designing nighttime lighting equal to natural daytime lighting or even equal to the lighting in interior spaces. As a result, they must create the best nighttime visibility possible within the limits of practical design. One important step in this process is to identify the factors that affect visibility.

Based on results of previous studies, The Illuminating Engineering Society of North America developed a proposed calculation procedure for lighting design based on visibility. The IESNA visibility calculation procedure does not, however, take into account the color output of the light sources, although they acknowledge its importance in their report. Recent research shows that the color output of the light sources used for roadway lighting has a significant effect on how well we see at night. Moreover, vision scientists have known for most of the twentieth century that the eye's response to color depends upon the amount of light available. Nevertheless, this important fact is often ignored when we measure the lumen output of a light source.

A lumen or not

Lumens are the standard measure of light output. Lamp manufacturers and lighting professionals generally assume that all lumens are equal in terms of the visibility they create. This assumption can be proven incorrect.

Standard measures of defining and measuring lumens provide a rated lumen output for a given lamp without considering that the eye sensitivity to the lumen output from a given light source varies, depending on the visibility conditions.

A true assessment of the lumen output of a lamp should be based on the eye's response to the visibility conditions. Since any given lamp type is used under many viewing conditions, numerous lumen output values can be calculated for that lamp depending upon which condition is present.

When the light level is very low, the viewing conditions are no longer photopic (high light levels). Instead, they are referred to as scotopic. Typical scotopic conditions are starlight levels at night. In between photopic and scotopic, mesopic conditions refer to twilight and typical street lighting levels.

Under scotopic conditions, the eye's visual response changes dramatically. The eye's sensitivity to yellow and red light is greatly reduced, while the response to blue light is greatly increased. Clearly, if lamp lumen output under scotopic viewing conditions has been determined using photopic measurements, the lumen output value does not accurately measure the true amount of light produced by the lamp.

In reality, the eye response does not shift suddenly from photopic to scotopic conditions. A gradual change occurs as light levels are reduced. This twilight zone is the mesopic condition in which the eye's response lies somewhere between photopic and scotopic.

The change in the eye's spectral response is due to the presence of two types of light receivers in the retina of the eye. One receiver is called rods and the other, cones. Cones are active at high light levels and are located mainly in the central part of the human field of view. When we look directly at an object, we are using our cone receivers. The cones respond to photopic light.

The rods are responsible for human vision at low light levels and are located in the peripheral field of view, away from our direct line of sight. As the light level reduces, cones become less active, rods become more active. The rods are sensitive to scotopic light.

Under nighttime driving conditions, both rods and cones are active. Objects viewed directly by the eye are seen by the cones. Peripheral objects are seen primarily by rods. Peripheral objects may be a car approaching down a side road or a child running towards the roadway. Rod vision is obviously very important in night driving.

Color and lumens

As an illustration, the blue output of an incandescent lamp is low. The eye sensitivity to blue light under photopic conditions is also low. The blue output of this lamp therefore produces few lumens under photopic conditions. The red power of the lamp is very high, but the response of the eye to red under photopic conditions produces only moderate lumens. On the other hand, the yellow output of the incandescent lamp is moderate, but the eye's sensitivity to yellow light under photopic conditions is very high. As a result, the yellow output of the lamp produces much of its lumens. This is why an incandescent lamp produces a slightly yellowish light, even though its main output is red.

With this understanding, the high lumen output of high-pressure sodium lamps can be readily explained. Sodium produces light that is primarily yellow. The eye sensitivity to yellow under photopic conditions is very high. As a result, high-pressure sodium lamps have high lumen ratings as perceived by the eye. On the other hand, under scotopic conditions, the effective lumens are greatly reduced because sodium produces very little blue and green light.

These effects with low-pressure sodium lamps are even more dramatic. Almost all energy output with this lighting source is in the yellow region, giving very high photopic lumen output. At low light levels, LPS has drastically reduced effectiveness.

The lumen output of a lamp is modified when the shifting color sensitivity of the eye at low light levels is taken into consideration. The term effective lumens can be used for this modified lumen output. The effective lumens will be different from the measured photopic lumens.

Metal halide lamps

A typical metal halide lamp has strong light output in the blue, green, and yellow regions. The result is a high lumen output for this light source at all light levels. The blue light output of metal halide is in the high sensitivity region of the eye for low light levels. This means that the effective lumens actually increase for a metal halide lamp as the light level reduces the eye shifts to a blue/green peak sensitivity.

As the light level diminishes from photopic, through meso-pic, to scotopic conditions, the effective lumens of yellow light sources are reduced and the effective lumens of blue/green sources increase. But has this effect actually been demonstrated in real life situations?

Several research projects conducted with human subjects support these conclusions. For example, Dr. Alan Lewis, Dean of the Michigan School of Optometry, and his colleagues conducted vision experiments using various light sources, including mercury, metal halide, high- and low-pressure sodium and incandescent. The tests were carried out over a range of lighting levels from photopic down through mesopic to scotopic.

In the first series of tests, the ability of the eye to see the difference, or the contrast, in brightness between an object and its background was measured under different conditions. In one experiment, the subjects were shown a grating where the amount of contrast between the lines in the grating was varied. Five different light sources were used to light the grating. Under the metal halide source, the ability to detect fine contrasts is significantly better than under sodium sources.

Other experiments measured the reaction time of the test subjects, meaning how fast they were able to distinguish contrasts. The tests were conducted under different light sources, and the light levels were varied. In one test, the subjects were required to identify whether a grid of lines was horizontal or vertical under a wide range of light levels. In another study, subjects were shown a photographic transparency of

a woman standing at the side of a roadway near trees and a fence. In some cases, the woman in the photograph was facing the roadway while in other cases she was facing away from the roadway. Test participants were required to identify which way she was facing, and the time it took them to make this identification was recorded.

At low street lighting levels, there is considerable difference in results for the various light sources. The reaction times for high-and low-pressure sodium are roughly 50% longer than for metal halide. These results clearly demonstrate that the color output of a light source has an important influence on visibility and that the effects are real and significant.

Effectiveness of lamps

In other tests, Dr. Lewis has compared the response time of test subjects under different light sources. Dr. Lewis has evaluated sources at both high and low street levels for the same reaction time and task. The testing was conducted first at a fairly high street lighting level such as might be found on major roadways. Since Dr. Lewis has found metal halide to be the most effective source, he used it as the basis of comparison.

His results indicate that a high-pressure sodium lighting system needs to produce a light level 3.9 times higher than metal halide, to be equivalent to a metal halide system, under the test conditions evaluated. For low-pressure sodium, 4.8 times more light is required to be equivalent to the metal halide level.

Dr. Lewis conducted similar research at low light levels found in fairly dark areas of a roadway. This may be the most significant data of all, because accidents are more likely to occur in dark areas. Such dark areas are also common off the roadway in areas where a driver needs to detect a hazard approaching from the side using peripheral vision.

These results show that 7.8 times as much high-pressure sodium luminance must be provided to be equivalent to metal halide. For low-pressure sodium, 14.6 times the light level must be produced to be equivalent to metal halide light. A high-pressure sodium lighting system will require approximately 6 times the luminance level of an equivalent metal halide system. Consequently, a roadway lighting system powered by 150-watt metal halide lamps will be equivalent to a high-pressure sodium system using lamps of six times the lumen output. The initial lumen output of a 150-watt metal halide source is 15,000 lumens, and therefore the high-pressure sodium lamp for equivalent visibility under the described conditions must have an output of 90,000 lumens. This would require high-pressure sodium lamps of about 700 watts to match the 150-watt metal halide lamp. Even assuming a faster lumen depreciation for metal halide versus high-pressure sodium, this is a huge difference.

The comparison between metal halide and low-pressure sodium lighting showed that between roughly 8 and 14 times as much light is required from the LPS system to have the same effectiveness as metal halide under these conditions.

The 6 times greater average luminance level of halide versus high-pressure sodium occurs where it is strongly needed, that is, in side or peripheral viewing and dark areas, where otherwise hidden hazards may be present. The increased visual effectiveness of white light with a high blue/green content under these nighttime conditions is dramatic. The powerful, independent data, which has been corroborated by several researchers, is worthy of serious consideration by roadway lighting design professionals.

Dr. Ian Lewin is founder of Lighting Sciences Inc. and President of Lighting Professionals Inc. of Scottsdale, Arizona, USA, now a part of [Advanced Lighting Technologies Inc.](#)