ROAD LIGHTING

M. Helal discusses various options that need to be weighed when choosing the appropriate source for ideal roadway lighting levels.

Several research projects have been conducted in recent years to determine whether the spectral distribution of the light source has any effect on the visibility it produces. Research has been conducted at low levels typical of roadway lighting and also at higher levels typical of the lighting of interior spaces.

Results have demonstrated that the lamp spectral distribution influences human perception in several different ways. Some effects are significant only at low light levels, while others may be important at higher levels.

This article summarizes some of the work and illustrates how the distribution of lamps influences vision at low light levels.

Highway visibility

Nighttime visibility is a critical issue to users of our highways and to those involved in street lighting design. Roadway accidents occur at a substantially higher rate during night hours versus daytime. While there are multiple reasons for this, it is widely believed that the main cause is the reduced visibility caused by the low levels of light that prevail. It is not economically or technically feasible to produce nighttime lighting to match the quantity or quality of outdoor day-lighting, or even the lighting typically found in interior spaces. It is essential, therefore, to enhance nighttime visibility to the greatest extent possible within the limitations of practical designs. Factors which affect visibility are of considerable concern.

A major area of research work in nighttime visibility is the development of a method of calculating and specifying the visibility of roadway hazards at night. This has been previously addressed. Methods have been developed to determine the luminance contrast between a small target representing a hazard on the roadway and the background against which it is seen. Glare from streetlights is also taken into account. By such calculation, small target visibility (STV) can be assessed indicating how well the hazard can be seen under specified conditions. While much work is still to be done, enough is known to have allowed the IESNA to develop a proposed recommended practice which is based on visibility. Use of the new procedures will not be mandatory, but the first major step toward visibility-based lighting design has been taken.

A major factor, however, is not considered in the IESNA visibility calculation procedure (although its importance is acknowledged). This concerns the spectral distribution, or color, of the light sources used for roadway lighting which is emerging in recent research as having a significant effect on how well we see at night.

This article provides a brief summary of some of the theory and practice involved. Considerably more detail is available through the proceedings of the Symposium on Vision at Low Light Levels, Orlando, Florida, and May 1998.

When is a Lumen not a Lumen?

It has been generally assumed by all lamp manufacturers and lighting practitioners that all lumens are equal in terms of the visibility they create. Upon examination, however, the assumption proves to be false.
Methods of defining and measuring lumens date back to the 1920s when the International Commission on Illumination (CIE) V (l) curve were established. V (l) is the eye sensitivity curve which relates visual response to the wavelength of the light source). Vision scientists have known for most of the twentieth century that the way in which the eye responds to color is dependent upon the lighting conditions. Under certain conditions, the eye may perceive effects of high lumen output from a given light source. Under different conditions, the lumen output may be seen by the eye as much higher or much lower. Lamps, however, are given a rated lumen output as if the eye sensitivity to the light output of any particular lamp was always identical.

The problem is further compounded when we realize that all other lighting quantities, upon which we base our lighting design calculations, are derived from the assumed lumen output of the lamp. These include lax and foot-candles, intensity or candlepower, and luminance (cd/m^2).
Because the eye varies in its response to different wavelengths of light under differing conditions, true assessment of the lumen output of a lamp should be based on the eye's response to the conditions under which the lamp is being used. Further, as any given lamp type is used under many conditions, there are numerous applicable lumen output values for that lamp dependent upon the conditions of use.

How Are Lamp Lumens Determined?

Both in theory and in practice, the determination of lamp lumens involves knowing the spectral power distribution (SPD) of the lamp and the visual response of the eye. Light is defined as energy as evaluated by the human eye. Light is not simply defined as energy in the same way as other forms of radiation. It is defined as the visual effect created by that energy. To "simplify" matters, in 1924, the CIE adopted the standard response curve, V (λ), which defines the spectral response of a typical person under "photopic" conditions. (Photopic refers to high light levels typical of daylight and interior lighting.) The V (λ) curve also is applicable only to the center small area of the eye's field of view.
To determine lamp lumens, the power of the light at each wavelength, l, in the visible spectrum is multiplied by the V(λ) value or eye sensitivity at the equivalent wavelengths. Then all of these multiplied values are summed to find the lumen output. This may be stated as:

Lamp Lumens =
K ∑ Lamp Power (λ). V (λ). ❋ λ

Where K is a constant to account for units.

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

When Is the V (λ) Curve not applicable?

So long as the V (λ) function is accurate and applicable to the viewing conditions being

considered, the lamp lumen value is accurate. If viewing conditions change, however, and V (λ) is no longer applicable, the lamp lumen figure will not be indicative of the effective light output of the lamp.

High light level conditions, where luminances are generally in excess of 3 cd/m^2, are termed "photopic levels." The V (λ) curve applies to such conditions. When the light level is very low, say below 0.001 cd/m^2, the conditions are "scotopic." This is typical of starlight levels at night. Between these two, conditions are referred to as "mesopic," and refer to twilight and frequently used street lighting levels. Under scotopic conditions, the eye's visual response changes dramatically.. This effect has been known for over a century and is called the Purkinje shift. 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 has been determined using the photopic V(λ) curve, but viewing conditions are scotopic, the lumen output value will not give an accurate indication of the effective amount of light produced. The eye response does not shift suddenly from photopic to scotopic conditions. It undergoes a gradual change as light levels are reduced. This twilight zone is termed "mesopic." The eye's mesopic response lies somewhere between photopic and scotopic.

Rods and Cones

the change in the eye's spectral response can be explained by the presence of two types of receptors in the retina, rods, and cones. Cones are active at high light levels and are most densely situated in the central part of the field of view. When we look directly at an object, we are using our cone receptors. The spectral response of the cones corresponds to the photopic V (λ) sensitivity curve.

The rods are responsible for human vision at low light levels and are prevalent in the peripheral field of view, away from our direct line of sight. As the light level reduces, cones become less active, rods become active. Spectral sensitivity gradually switches towards the scotopic response curve.

During practical driving at night, both receptor types are active. Objects viewed directly by the eye are seen by the cones. Off-axis objects are seen primarily by rods. Such off-axis objects may be a car approaching down a side road, or a child running towards the roadway. Rod vision and its associated spectral response are obviously very important in the night driving situation.

Effective Lumens

we can use the term "effective lumens" to define the modified lumen output of a lamp taking into account the shifting color sensitivity of the eye at low light levels. To find the effective lumens of the incandescent light source the lamp power at each wavelength is multiplied by the scotopic eye sensitivity, at each wavelength, and then the values are summed. The effective lumens, therefore, will be different from conventional photopic or "raw" lumens.

Sodium Lamps

the reason for the high lumen output of the high pressure sodium lamp immediately becomes apparent. The maximum energy output of sodium lies in a yellow region where the eye sensitivity is very high. Because the lumen is defined as the amount of light as perceived by the eye under photopic conditions (bold curve), high pressure sodium lamps have high lumen ratings. It is not so much that the sodium lamp produces a high output of energy, but rather that its energy peak is near the maximum photopic sensitivity wavelength of the eye.

Note that very little energy output of the high pressure sodium lamp occurs at wavelengths shorter than the peak. Therefore the effective lumens for scotopic conditions (dashed curve), is greatly reduced. Sodium produces very little blue and

green light, and therefore its effectiveness under low light levels is considerably reduced.

These effects with the low pressure sodium lamp are even more dramatic. Virtually all energy output is in the yellow region, giving very high photopic lumen output. At low light levels, however, there is almost no energy output at wavelengths where the eye is sensitive. Therefore, low pressure sodium has drastically reduced effectiveness at such light levels.

Metal Halide Lamps

Note that with metal halide lamp lighting there are strong peaks in the blue, green, and yellow regions. Note also that there is a considerable "continuum or energy output at all wavelengths in addition to the peaks.
When the energy output curve of the metal halide lamp is multiplied by the photopic sensitivity curve, a high lumen output is found, although not quite as high as HPS. Using the dashed curve for scotopic conditions, it will be seen that peaks in the metal halide energy output lie in the high sensitivity region of the eye for low light levels. Moreover, the strong continuum of blue/green energy also lines up with the maximum height of the scotopic eye sensitivity curve. The net result is that the effective lumens increase for a metal halide lamp as the light level reduces and the eye shifts to a blue/green peak sensitivity.

Practical Vision Experiments

the above theory tells us that as the light level reduces from photopic, through mesopic, to scotopic conditions, the effectiveness of yellow sources reduces and that of blue/green sources increases. Can this actually be demonstrated in practice? Several research projects have been carried out with human subjects to find whether these effects are real and demonstrable. The results of various researchers are in general agreement. The work of Dr. Alan Lewis, Dean of the Ferris State College of Optometry, shows the effects very clearly. [4] He and his colleagues conducted vision experiments using various light sources: mercury, metal halide, and high and low pressure sodium. Incandescent was also included as a reference base. Tests were carried over a range of lighting levels from photopic down through mesopic to scotopic.
In the first series of tests, "contrast threshold" of the eye was measured under differing conditions. A primary requirement for human vision is the ability to see contrast, which is provided by the difference in brightness between an object and its background. When contrast threshold is reduced, the eye is able to distinguish smaller contrasts. Thus a lower contrast threshold indicates increased visibility, other factors being equal.

The results indicate that for luminance of 3 cd/m^2 and less, there is a divergence in the results for the different light sources. Under the metal halide source, the ability to detect low contrasts is substantially better than under sodium sources.
In further experiments, the reaction time of subjects was measured. In one case, the subjects were required to identify the orientation of a grid of lines, horizontal or vertical, over a wide range of light levels. In another test the visual task was a photographic transparency of a woman standing at the side of a roadway in the presence of trees and a fence. In some cases, the woman was facing the roadway while in other cases she was in an identical position but facing away from the roadway. Subjects were required to identify which way she was facing, and their time to make this identification was recorded.
Examining different street light sources indicates that at street lighting levels below 3 cd/m^2, there is considerable divergence in results for the various light sources. At 0.1 cd/m^2, reaction times for high and low pressure sodium are roughly 50 percent longer than for metal halide.
These results clearly demonstrate that the concept of spectral qualities of a light source having an influence on visibility is not merely theory. Practical visual experiments show that the effects are real and significant.

Other Research

Further work by Lewis has compared the efforts of other researchers.5 It has been shown that these other scientists have produced results for mesopic vision sensitivities very similar to those developed by Lewis.

The Effectiveness of Lamp Types

In further testing, Lewis has computed the comparative effectiveness of light sources of different types in producing a given reaction time. For example, let us say that light source A produces a reaction time of 800 msec in identifying a particular hazard at a level of 0.1 cd/m^2. Let us say also that a different light source B needs to produce a lighting level of 1 cd/m^2 to create the same 800 msec reaction time. Light source B then has a multiplier of 10 versus source A; that is, 10 times the lighting level must be produced by source B to be as effective as source A.
Lewis has evaluated sources at both high and low street lighting levels for the same reaction time task (a pedestrian at the curb).5 Such multipliers for the various sources were calculated.

High Street Lighting Levels

testing was first conducted at a level of 1 cd/m^2. This is the luminance (or reflected light level) corresponding to a fairly high street lighting level such as might typically be found on major roadways. As Lewis has found metal halide to be the most effective source, it was used as the basis of comparison and given an effectiveness of 1.0. Table 1 shows lumen effectiveness multipliers for all five sources tested.

Table 1— Comparison of Light Sources High Roadway Lighting Level

Source	Required Lumen Multiplier*
Metal Halide	1.0
Incandescent	1.5
Mercury	2.4
High Pressure sodium	3.9
Low Pressure Sodium	4.8

*Light level multiplier needed to produce the same reaction time as metal halide (for when metal halide provides a lighting level of 1.0 cd/m2).

Table 1 indicates that a high pressure sodium lighting system needs to produce a level 3.9 times higher than metal halide, to be equivalent to a 1.0 cd/m^2 metal halide system, under the conditions evaluated. In other words, to produce the same reaction time for the realistic task, the high pressure sodium system must produce 3.9 cd/m^2 to be equivalent to the 1.0 cd/m^2 metal halide system.
For low pressure sodium, 4.8 times more light is required to be equivalent to the 1.0 cd/m^2 metal halide level, i.e., 4.8 cd/m^2 is needed.

Low Street Lighting Levels

Lewis similarly conducted research at luminance levels of 0.1 cd/m^2, equivalent to low 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 prevalent off the roadway in areas where a driver needs to detect a hazard approaching from the side using peripheral vision.

Table 2— Comparison of Light Sources Low Street Lighting Level

Source	Required Lumen Multiplier*
Metal Halide	1.0
Incandescent	2.9
Mercury	4.4
High Pressure Sodium	7.8
Low Pressure Sodium	14.6

*Light level multiplier needed to produce the same reaction time as metal halide (for when metal halide provides a lighting level of 1.0 cd/m2).

Table 2 presents results, giving the multipliers for other light sources required to be equivalent to a 0.1 cd/m^2 level of metal halide.

As can be seen from Table 2, 7.8 times as much high pressure sodium luminance must be provided. That is, to be equivalent to 0.1 cd/m2 of metal halide lighting, 0.78 cd/m^2 of high pressure sodium is needed.

For low pressure sodium, 14.6 times the light level must be produced to be equivalent to 0.1 cd/m^2 of metal halide light.

Metal Halide versus High Pressure Sodium

Street lighting levels generally range from 0.1 cd/m^2 in dark areas of roadways which are lit to minimum standards, to about 1.0 cd/m^2 average for roadways lit to a high standard. Therefore the data presented in Tables 1 and 2 have a general applicability to street lighting. The multipliers for high pressure sodium versus metal halide range broadly from about x4 to x8. Lewis' work suggests that perhaps a value of x6 can be regarded as an appropriate average.

Using this figure to address visibility under the conditions described, a high pressure sodium lighting system will require approximately 6 times the luminance level of an equivalent metal halide system. Thus, a roadway lighting system powered by 150 W metal halide lamps will be equivalent to a high pressure sodium system using lamps of six times the lumen output, other factors being equal. The initial lumen output of a 150 W metal halide source is 15,000 lm, and therefore the high pressure sodium lamp for equivalent visibility under the described conditions must have an output of 90,000 lm. This would require high pressure sodium lamps of about 700 W to match the 150 W metal halide.

Even assuming a faster lumen depreciation for metal halide versus high pressure sodium, it can be seen that there is a huge factor involved.

In making a comparison between metal halide and low pressure sodium lighting, between roughly 8 and 14 times as much light is required from the low pressure sodium system to have the same effectiveness as metal halide, for the conditions evaluated.

As indicated earlier, the effects described do not apply directly to the center of the field of view (although other beneficial effects of blue/green sources possibly do). The x6 average advantage of metal halide versus high pressure sodium occurs where it is strongly needed: in off-axis viewing and dark areas, where otherwise hidden hazards may be present. The increase in the visual effectiveness of white light with a high blue/green content is dramatic. The powerful, independent data, which has been corroborated by several researchers, appears worthy of serious consideration by design professionals.

High Power CFL

E new arrival for street road lighting is the high power CFL T5 lamps that can offer dramatic high lumen/watt close to metal halide (95~105 lumen/watt) with reasonable lumen depreciation in comparison with metal halide lamps in addition to economic cost value, new experiences are indicating that high power CFL lamps will be used widely for road lighting.

The new 3C technology used in CFL powder that gives desired Kelvin in addition to the absence of high heat produced from HID lamps will allow the new technology to replace conventional Sodium and Metal Halide lamps ..

References

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