Lamp Color and Visibility in Outdoor Lighting Design

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Introduction

Outdoor lighting has several fundamental purposes. It plays a role in crime prevention, improvement of the nighttime environment, and in providing increased safety. Fundamental issues of visibility relate particularly to security and safety. Enhanced security is provided by improved visibility, and the night driving task is safer if the motorist can see well.

Figures for the United States indicate approximately 40,000 road fatalities per year. Per 100,000 miles driven, the nighttime accident rate on unlighted highways is roughly three times that during daylight hours. While this is partly alcohol and fatigue related, the major factor is believed to be the reduced visual performance of the driver under night conditions. Statistics for other countries are probably similar.

While visibility is generally accepted as being linked to safety and security, defining visibility and the exact nature of the relationships is not easy. The issues are complex because the human visual system and its responses are complex. Producing desired visibility at night is limited by a host of technical and economic factors. Such factors need to be examined, understood and applied in the practical design of outdoor lighting. By doing so, methods may be developed to allow improved safety and security.

The Illuminating Engineering Society of North America has made considerable progress in defining the factors affecting visibility at night. The new IESNA/ANSI Recommended Practice for Roadway Lighting, publication RP8, defines a method for designing roadway lighting based on the visibility which it creates, rather than simply the amount of light a system provides.[1,2] This is a useful start. However, another important factor needs to be considered: The spectral distribution of the light source has been shown to be an important factor in visibility under outdoor lighting conditions. Being aware of this and making use of available information may allow increased safety and security without necessitating higher levels of light or power.

Spectral Characteristics of the Light Source

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, this proves to be a fallacy.

Methods of defining and measuring lumens date back to the 1920's when the CIE $V(\lambda)$ curve was established. (V-lambda is the eye sensitivity curve which relates visual response to the wavelength of the light source). However, vision scientists have known for most of the twentieth century that in fact 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 based on the assumed lumen output of the lamp. These include lux and footcandles, intensity or candlepower, and reflected light, i.e. luminance, (candelas / sq. meter). See sidenotes.

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 under the conditions under which the lamp is used. Further, as any given lamp type is used under many conditions, there are numerous applicable lumen output values for that lamp, all dependent upon the conditions of use.

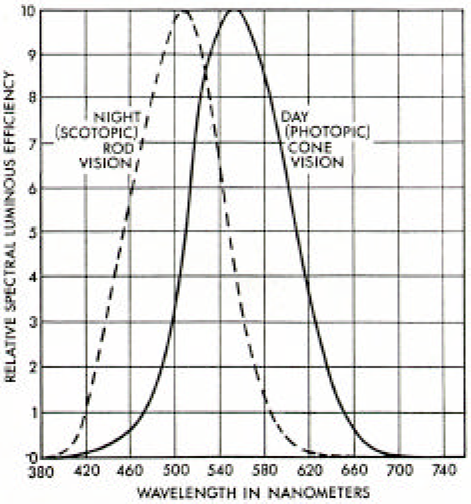


Figure 1: The V(λ) curve (bold) for photopic vision, and the V'(λ) curve (dashed) for scotopic vision.

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*. Thus 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 1935, the International Commission on Illumination (CIE) adopted the standard response curve, V(λ), which defines the spectral response of a typical person under "photopic" conditions. Figure 1, bold curve. "Photopic" refers to high light levels typical of daylight and interior lighting. Note also that the V(λ) curve is applicable only to the center small central area of the eye's field of view.[3,4]

To determine lamp lumens, the power of the light at each wavelength, λ, 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:

$$\text{Lamp Lumens} = K \sum \text{Lamp Power}(\lambda) \,.\, V(\lambda) \,.\, \Delta\lambda$$

K is a constant to account for units.

Figure 2 shows the spectral graph of an incandescent lamp on the same wavelength scale as the eye sensitivity curves beneath it. As we can see, an incandescent lamp's power is low in the blue part of the spectrum; Figure 1 also shows that the photopic eye sensitivity to blue light is low. The blue output of this lamp therefore produces few lumens. The red power of the lamp is very high, but the 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, although in fact its main output is red.

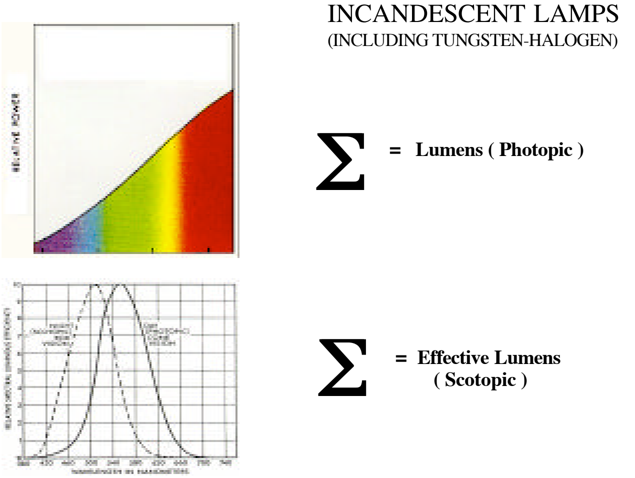


Figure 2: The typical power distribution for an incandescent lamp.

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/sq.m., are termed “photopic" levels. The V(λ) curve applies to such conditions. But when the light level is very low, say below 0.001 cd/sq.m., the conditions are described as “scotopic.” This is typical of starlight levels at night. Between these two, conditions are referred to as “mesopic”, and apply to twilight and frequently used street lighting levels. Figure 3 illustrates the ranges.

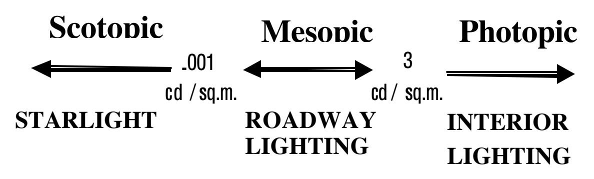


Figure 3: The range of photopic, mesopic and scotopic light levels.

Under scotopic conditions, the eye’s visual response changes dramatically (see Figure 1, dashed curve). 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 through the "mesopic" twilight range. 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 levels decrease, the cones become less active, the rods become active and 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.

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 shown in figure 2 at scotopic levels, for example, the lamp power at each wavelength is multiplied by the scotopic eye sensitivity (the dashed curve in Figure 1) at each wavelength. Then the values are summed. The effective lumens, therefore, will be different from convenional photopic or “raw” lumens.

Sodium Lamps

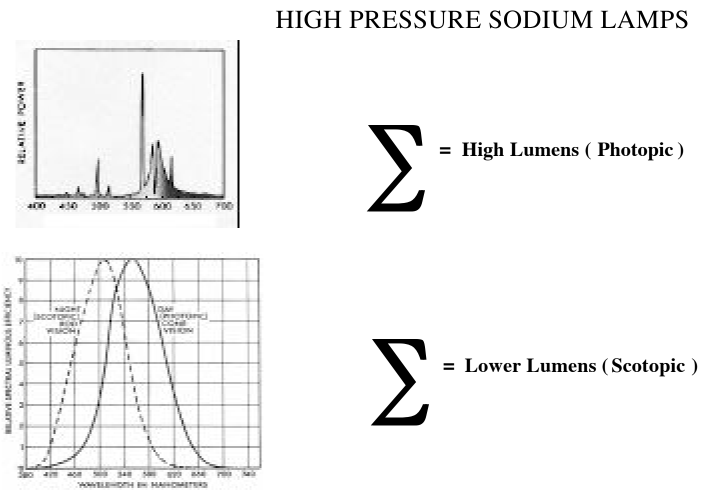


Figure 4: Spectral Power Distribution of a typical high pressure sodium (HPS) lamp.

Figure 4 shows the spectral power distribution of a typical high pressure sodium (HPS) lamp, drawn to the same wavelength scale as the eye sensitivity curves beneath it. The reason for the high lumen output of the HPS 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 (the bold curve), HPS 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 HPS lamp occurs at wavelengths shorter than the peak. Therefore the *effective lumens* for scotopic conditions (the dashed curve) is greatly reduced. Sodium produces very little blue and green light, and therefore its effectiveness under low light levels is considerably reduced.

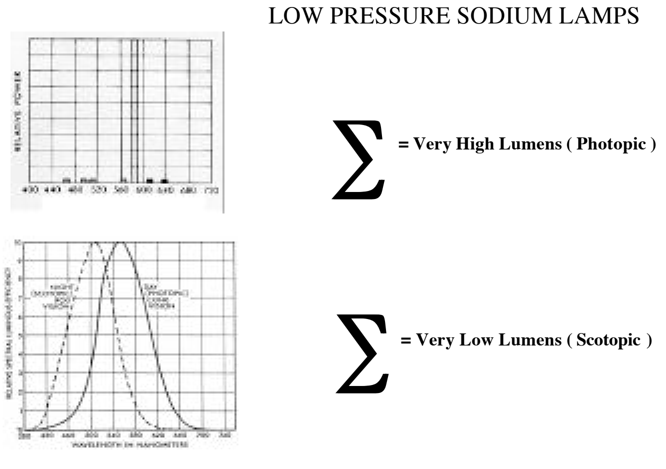


Figure 5: Spectral Power Distribution of a typical low pressure sodium (LPS) lamp.

The effect with the low pressure sodium (LPS) lamp is even more dramatic, as can be seen from Figure 5. 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 most sensitive. LPS lamps therefore have drastically reduced effectiveness at such light levels.

Metal Halide Lamps

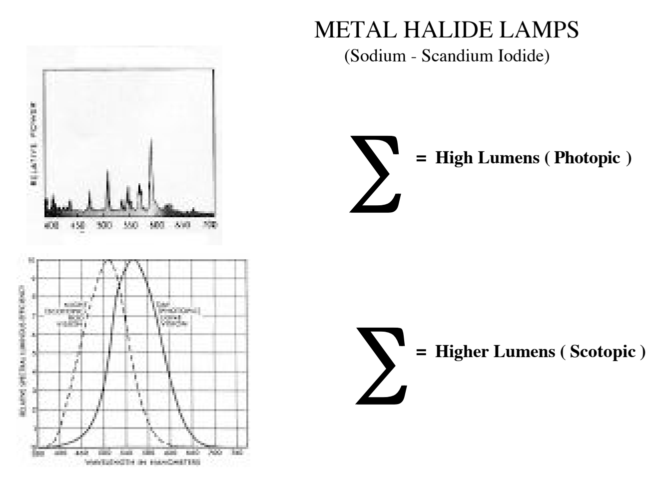


Figure 6: Spectral Power Distribution of a typical metal halide lamp .

Figure 6 shows a typical metal halide energy output. Note that there are strong peaks in the blue, green and yellow regions. Note also that there is a considerable “continuum” of 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 strength 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 (see Figure 6).

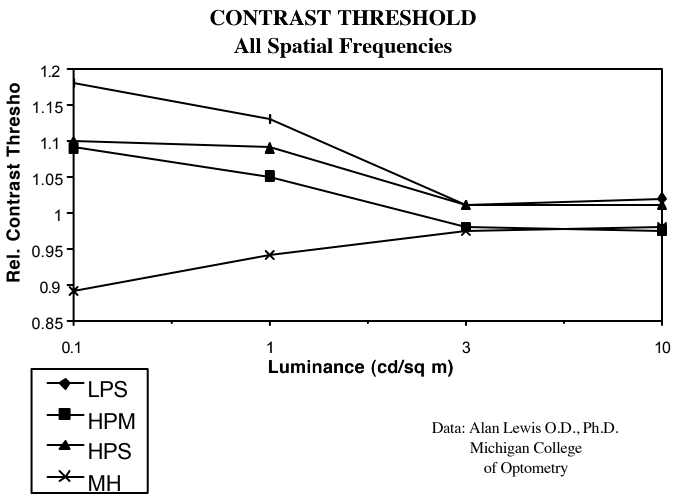
In summary, under mesopic viewing conditions, yellow sources have reduced effectiveness while blue/green sources have increased effectiveness.

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 falls 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 Michigan School of Optometry, shows the effects very clearly.[5] He and his colleagues conducted vision experiments using mercury, metal halide, high and low pressure sodium light sources. 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, the “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, this indicates that the eye is able to distinguish smaller contrasts. Thus a lower contrast threshold indicates increased visibility, other factors being equal.



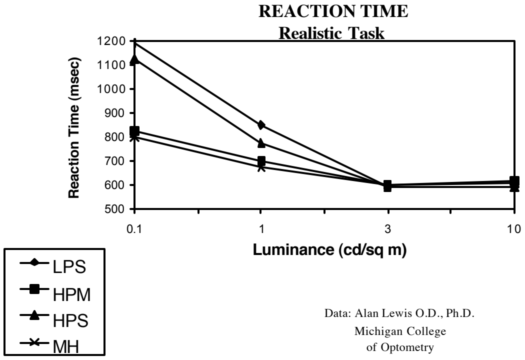
Data: Alan Lewis O.D., Ph.D.
Michigan College
of Optometry

Figure 7. Contrast thresholds measured under different light sources.

Figure 7 shows results for subjects exposed to a contrast grating, where the degree of contrast between the grating lines was varied. Various different light sources were used to light the grating. The results indicate that for luminance of 3 cd/sq.m. 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, possibly to step in front of the driver, 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 - their time to make this identification was recorded. Figure 8 presents results for the different light sources.

Examining Figure 8 indicates that at street lighting levels below 3 cd./sq.m., there is considerable divergence in results for the various light sources. At 0.1 cd/sq.m., the reaction times for high and low pressure sodium are roughly 50% longer than for metal halide. This clearly demonstrates that the concept of spectral qualities of a light source having an influence on visibility is not merely theory. Practical vision experiments show that the effects are real and significant.



Data: Alan Lewis O.D., Ph.D.
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of Optometry

Figure 8. Reaction times measured under different light sources.

Important Questions

Because engineers who have performed outdoor lighting designs in the past have ignored the effects of lamp spectral distribution, this information is rather startling. However, in terms of what we have known about the eye's spectral response for many years, perhaps we should not be surprised.[4]

In considering this subject, it becomes apparent that some key questions need to be addressed:

- Are the lighting conditions typically existing at night sufficiently low that a mesopic eye response should be used?
- If mesopic conditions apply, does the shift to blue/green sensitivity apply universally to everything the eye sees?

- If the enhancement effects caused by blue/green sources affect only certain tasks, what are they and how do they relate to accidents?
- Under practical circumstances, what is the magnitude of these effects? Are they minor or highly significant?
- What are the effective lumen ratings for available light sources under actual outdoor lighting conditions?

Are Typical Nighttime Lighting Levels Mesopic?

It is normally assumed that when luminances exceed 3 cd/sq.m., conditions are photopic, and rarely is the luminance of a roadway as high as 3 cd/sq.m. Designs performed to international standards are likely to have lighting levels in the general range of 0.3 to 2.0 cd/sq.m. Therefore, mesopic effects can be detected when light levels are typical of roadway lighting systems.

In the United States of America, the recommended average luminance for major commercial roads is 1.2 cd/sq.m.[1] For local residential roads, the average level is 0.3 cd/sq.m. Other roadway classifications fall within this range.

A survey of actual roadway luminance values conducted in Albany and Troy, New York, USA, showed a range from 0.74 to 0.013 cd/sq.m.

It is clear, therefore, that roadway lighting levels fall in the range of luminances which are classified as mesopic. The mesopic visual effects therefore should be taken into consideration for proper design.

Another factor needs to be addressed: hazards to the driver frequently are positioned off the highway. A vehicle may be approaching from a dimly lighted side road. An animal may be running towards the roadway in an essentially unlighted area. There is evidence to suggest that many accidents are caused in this way. (In the USA, deer which leap out of dark areas onto the road are a major cause of serious collisions). Luminaires designed for roadway lighting typically concentrate light onto the road itself, and surrounding areas may be lighted only by spill light. Off roadway light levels may fall to 10% or less of the roadway luminance. Even where a surround ratio, SR, is specified in order to ensure some lighting of the surrounds as in international standards, it applies only to a strip "just outside the edges" of the driving lane.

Lighting levels of the general surrounding areas may possibly be 0.1 cd/sq.m. or less, at which very major spectral effects have been shown.[4,5,6,7,8,9,10,11]

Does the Shift to Blue/Green Sensitivity Apply to the Whole Scene?

The human eye is exceedingly complex. As mentioned there are two main forms of receptors, the rods and cones. In summary, cones provide visibility under photopic conditions, and their spectral response is the basis for the photopic eye luminous efficiency curve, $V(\lambda)$, used to determine lamp lumen ratings. This curve applies only to the center 2° field of vision, yet is used almost universally as if it were applicable to the entire scene. Cones are concentrated in the part of the retina corresponding to this center field of view, or "fovea". The density of cones diminishes progressively away from the fovea. Under scotopic light levels, cones are almost completely inoperative.

Rods provide vision under scotopic conditions. The spectral sensitivity of the rods corresponds to the scotopic luminous efficiency, $V'(\lambda)$, function. As the density of cones diminishes away from the fovea of the retina, the density of rods increases.

Under mesopic conditions, both rods and cones are active. Central, or foveal, vision is cone dominated. Peripheral vision is rod dominated. Vision just off the central field of view uses both rods and cones. Visibility improvement by the use of blue/green sources therefore may be insignificant for direct on-axis viewing, but very significant for just off-axis (i.e. outside the very narrow 2° central field) and peripheral detection. The extent of the spectral effects therefore is dependent on the location of task being detected.

Off-axis Tasks and Driver Safety

If on-axis tasks are unaffected by the spectral distribution of the light source but off-axis tasks are highly affected, it is relevant to ask whether peripheral vision is important in the driving task. If the detection of off-axis tasks has a significant effect on safety, then these spectral effects are also significant.

In a very practical sense, the importance of off-axis viewing is easily demonstrated. Imagine you are driving at night, but you have a black tube in front of each eye. Figure 9. The tubes move with your eyes as you glance around, always aligned in your viewing direction. Suppose each tube is 1.75 inches in diameter, (the diameter of the cardboard tube inside a United States of America standard roll of toilet paper!). Suppose, however, that each tube is 50 inches long. Such a tube in front of each eye will restrict the observer's field of view to 2°. None of us would be prepared to drive at night with these black tubes in front of our eyes. To do so, even if it were possible, would completely eliminate peripheral vision, creating a highly dangerous situation by depriving the driver of essential visual information.

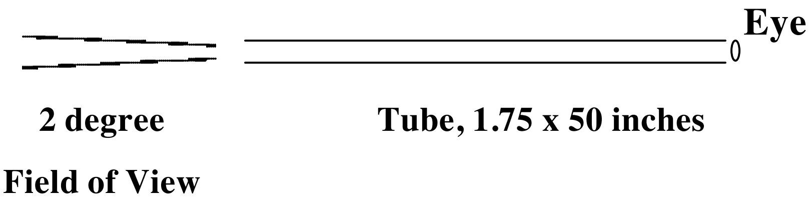


Figure 9. Demonstration of the central field of view.

This example serves to illustrate that it is intuitively obvious that peripheral vision is critical to the driving task.

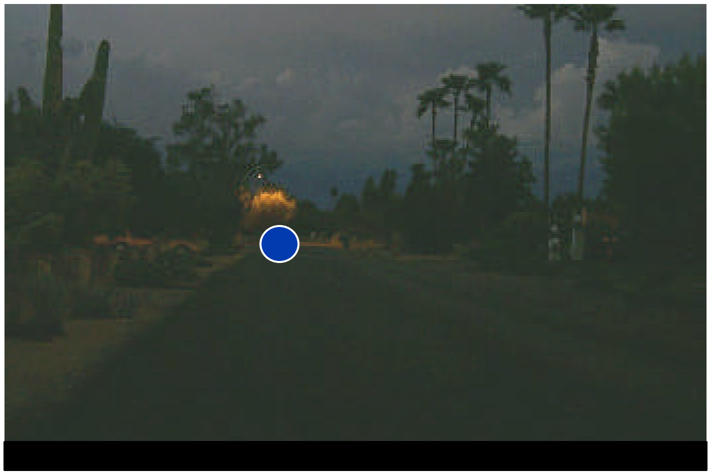


Figure 10. Illustration of the central field of view and off-axis vision.

Consider figure 10, a photograph of a dimly lighted nighttime residential scene. How much of this driver's view will be seen by the center or foveal field of view? The circle indicates this 2 degree zone. It is apparent that, although it is an important area, it constitutes a very small portion of what the eye sees. In fact, a great amount of information reaches the eye through off-axis vision, outside the 2° circle.

While a photograph cannot truly represent visibility, it is interesting to note that another vehicle is about to pull directly in front of the driver, entering the road from the side. A potential accident is ahead, and clear visibility is essential.

It has been argued that if a hazard is approaching the driver from the side, the driver will direct his line of sight to the hazard and view it foveally. The critical point is, however, that very often *initial detection occurs with off-axis vision*, then foveal vision will be used.[12] It is this early detection which is critical in accident avoidance. The ability of a driver to detect and respond to an object moving into the path of the vehicle has been shown to be primarily a peripheral vision function.[10] Also, the ability to maintain road position within a lane or to judge distance from a curb line also has been shown to be almost entirely based on peripheral vision.[13,14]

There is much evidence to support the fact that accident rates are related to the peripheral vision effects. In particular, off-axis vision is highly sensitive for detecting *changing conditions*. Movement of an object tends to be detected by the "macrocellular" channel of the human visual system, which is dominated by rod response, i.e. off-axis vision.

In a recent pilot study, subjects participated in a video projection game where a car was "driven" around various courses.[15] A computer monitored the time to drive each track and the number of crashes. Lighting levels tested were 0.1 and 1 cd/sq.m. Testing was conducted using the video image projected through a blue filter, and also through a red filter. At 0.1 cd/m^2, the number of crashes per mile reduced 7% for blue light versus red light, while the driving speed actually increased. This suggests the importance of the peripheral field as it is dominated by rods which have high blue/green sensitivity.

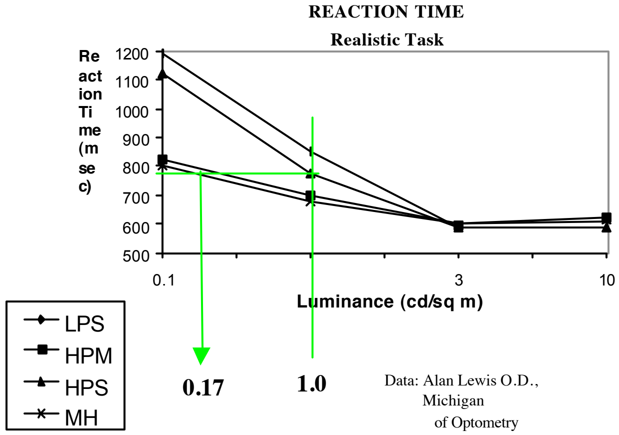
Although more research is warranted, there is clear evidence to support the reasonable assumption that off-axis vision is critical to the driving task. It is equally apparent that the spectral effects of the light source are also significant as they strongly influence the ability to perform off-axis tasks at low light levels.

On this matter, Professor Mark Rea of Rensselaer Polytechnic Institute has written "where visual flow is important to the performance of a task, using a spectral power distribution which is matched to the appropriate mesopic spectral sensitivity will lead to better task performance than a spectrum which is less well matched."

How Great Are the Mesopic Effects?

There is clear and compelling evidence to show that spectral effects can be highly significant in nighttime driving. Moreover, these effects are most significant under conditions where visibility may be worst, in low light level, off-axis situations which inherently constitute the most difficult conditions for hazard detection.

We can now ask, in terms of practical light sources, just how major are these effects. If metal halide sources enhance vision under these conditions versus sodium lamps, what multiplier should be applied to the lamp lumen ratings of the different lamp types to adjust for these visibility factors? Unfortunately there is no single answer. Any multiplying factor will depend on the location of the task, the nature of the task and the lighting level in the area of interest, amongst other factors. There is therefore a range of lumen modifiers which are dependent on the viewing conditions. Fortunately, research is available to allow broad quantification of the effects, which if used conservatively, should provide reasonable and defensible conclusions.



Data: Alan Lewis O.D., Michigan of Optometry

Figure 11. Determination of the effective metal halide level.

Reviewing Dr. Lewis' results for the realistic task, figure 11, we can develop conclusions on the effectiveness of different lamps for the conditions he tested. Drawing a vertical line at 1.0 cd/sq.m. and projecting another line horizontally from the high pressure sodium curve shows a reaction time of about 800 milliseconds. Dropping a vertical line from where the horizontal line intersects the metal halide curve yields 0.17 cd/sq.m. This indicates that, under these test conditions, 0.17 cd/sq.m. of metal halide light produces the same 800 millisecond reaction time as

1.0 cd/sq.m. of high pressure sodium. Thus metal halide is 6 times (1.0 divided by 0.17) as effective in this situation as high pressure sodium.

Other researchers have produced results which are less dramatic. Still others have shown even greater effects. This appears to be because the effects are dependent upon what test conditions are used, because many variables are involved.

Professor Werner Adrian has analyzed the data of Lewis and the basic research of others on brightness matching involving mesopic response functions.[6] He has developed rationale to indicate that the results of Lewis are as would be expected from known mesopic visual response functions. Calculations based on these functions correlate in their general form with Lewis' experimental data, although they appear to underestimate the full impact of Lewis' results.

Dr. Mark Rea and his associates have developed more conservative data applied to parking lot lighting and have studied the economics of the choice of light source.[16] For a system producing 0.1 cd/sq.m. average luminance, they estimate that the number of 400 watt HPS luminaires must be 50% higher than the number of 400 watt metal halide luminaires for equal perceived brightness.

He et al have presented results for reaction times to the appearance of a target located slightly off-axis.[7] Results show, for example, that reaction time for a high pressure sodium lighting level of 0.1 cd/sq.m. can be equated by metal halide lighting at 0.05 cd/sq.m. i.e. Double the level of HPS is needed to be equivalent to metal halide lighting.

The most dramatic data published so far is that of Dr. Lewis.

No matter which research results are reviewed, however it is apparent that significant factors are involved.

What Are the Effective Lumens for Practical Sources?

What do these research results mean in practical terms? How can the data be used by the design engineer? To answer these questions, we need to evaluate lamps in terms of their "effective lumens" and apply this in design calculations. To do this, the author proposes the use of "Lumen Effectiveness Multipliers," or LEM.
LEM values, once calculated, can be used as follows:

Effective Lumen Rating = Published Lamp Lumen Rating x LEM

This is a simple step in the outdoor lighting design calculation, such that the design then is based on the effective lumen rating.

Lumen Effectiveness Multipliers

We have seen that the rated lumens of a lamp are calculated by multiplying the measured energy at each wavelength by the photopic eye sensitivity for that wavelength, and summing the results. In just the same way, effective lumens can be computed by using a different eye sensitivity curve, that which is applicable to mesopic vision. The problem in doing so is that there are innumerable mesopic vision curves depending on the light level and the test conditions.

Professor Adrian's values are derived from brightness matching tests used to produce such a supplemental mesopic vision curve for a given condition. These tests did not involve reaction times or detection of movement; that is, they were not tests based on the visual performance of subjects in a real or simulated driving environment.

The work of Dr. Lewis and Dr. Rea more closely resembles realistic reactions such as a driver might experience. i.e. They used testing methods which evaluated *visual performance*. Where realistic task visual performance graphs are available, the Lumen Effectiveness Multiplier can be derived as described above using figure 11.

The empirical data of Dr. Adrian appear very conservative, particularly when compared to the much larger multipliers developed by Dr. Lewis using reaction time experiments. At this point in the development of the subject, however, perhaps it is prudent to use conservative values. The Lumen Effectiveness Multipliers provided in table 1 have been based upon data values derived by Dr. Adrian. As research progresses and more is known about nighttime driving tasks, these values are likely to be revised to incorporate the results of research based on new visual performance data. Evidence suggests that in the future, it will be justifiable to use perhaps considerably greater multipliers for metal halide and that even lower values must be applied to low pressure sodium lamps.

LEM values fundamentally are a comparison between two different light sources, and therefore there must be a base case for the comparison. High pressure sodium lighting is the commonest modern outdoor light source. It is generally accepted that lighting to meet certain specifications will fulfill the intent of those specifications when HPS is used. It is therefore logical to use HPS as our comparison base. The LEM values shown in table 1 are multipliers which indicate the effectiveness ratio of the stated light source versus HPS, for the given luminance levels. (It is assumed that these luminance levels have been calculated in the normal way, using photopic lumen ratings).

Table 1
Lumen Effectiveness Multipliers
vs. High Pressure Sodium

Luminance (cd/sq.m.	.001	.01	.1	1	3	10
Metal Halide	2.25	2.11	1.82	1.35	1.13	1.00
High Pressure Sodium	1.00	1.00	1.00	1.00	1.00	1.00
Low Pressure Sodium	0.47	0.51	0.78	0.82	0.95	1.00

Reviewing table 1, it can be seen that at a high light level of 10 cd/sq.m., higher than roadway lighting, the LEM values are 1.0. This is as would be expected as there are no mesopic effects involved.

When light levels are lower, however, the LEM values for Metal Halide increase and are above 1.0. By our definition, LEM's for high pressure sodium remain at 1.0.

For example, at a calculated luminance level of 0.1 cd/sq.m., the LEM value for metal halide is 1.82. Thus metal halide is 82% more effective than high pressure sodium for the conditions under which the data were derived. Low pressure sodium has an equivalent value of 0.78, and therefore is 22% less effective than high pressure sodium.

As the luminance level falls further, the LEM values change more.

The difficulty lies in selection of the LEM value to use. If the designer is purely concerned with direct on-axis tasks, or the light source is high pressure sodium, the chosen value should be 1.0. If the designer agrees that tasks which are off-axis by a few degrees and/or peripheral vision is important, then a luminance level should be selected and a value of LEM can be chosen for the applicable light source from table 1. In selecting the luminance level, using the average luminance of the road surface is probably invalid. Off-axis peripheral tasks are likely to lie in areas of lower luminance than the roadway. If the roadway has an average luminance of 1 cd/sq.m., the peripheral area lighted by spill light may have a luminance of perhaps 0.1 cd/sq.m. In really dark areas, very low luminances will be found and high values of LEM for metal halide are calculated. There needs to be much discussion of which luminance level should be chosen to be appropriate for given circumstances.

If the data of Dr. Lewis were to be used, much greater LEM values for metal halide would occur in table 1. His work has indicated that for metal halide at 0.1 cd/sq.m., roughly 8 times as much HPS light is needed, or 15 times as much LPS.[5] As discussed, this is believed to be because Lewis investigated realistic tasks involving performance reactions, while Adrian's work is derived from matching of perceived brightnesses.

Conclusion

It can be seen that a great deal of valuable information is available, much of which can be used now in practical lighting design. This does not suggest that the information and proposals presented are in any way perfect. There is much further work to be done.

In summary, we can draw a series of conclusions:

Nighttime vision under roadway lighting conditions is mesopic.
Effects are strong outside the 2° central field.
Off-axis vision is critical in night driving and is related to accidents.
Manufacturer's lamp lumens are not applicable to mesopic conditions.
The effects involved can be handled with "Lumen Effectiveness Multipliers" to provide a correction to published lamp lumens.

The research results found for metal halide effectiveness vary depending on the test situation. Where subjects are simply performing brightness matching between different light sources, metal halide has been shown to be about 10 to 100% higher in effectiveness than HPS. Where off-axis detection and reaction are involved, metal halide may be 6 times more effective than HPS, or even more.

New research involving movement and detection may show still greater effects.

Because the subject is complex, we should not take this as a reason to avoid these realities. Human lives are at stake in the nighttime driving situation. As professionals, we need to gain as much further information as we can, and apply what we already know. Improved safety and security are the likely results.

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Sidenotes

Illuminance, Luminance and Units

One thing is guaranteed when lighting matters are discussed: There will be confusion over units. However, the subject is not too complicated:

Illuminance. This is the amount of light *falling on* a surface, and is the traditional method of designing and measuring lighting.

Units of illuminance are:

Footcandle (English) = 1 lumen per square foot
Lux (Metric) = 1 lumen per square meter

Luminance. This is the light quantity *reflecting from* a surface. The eye sees this reflected light, and it is therefore a better measure of lighting level than illuminance. Many roadway lighting systems, particularly in Europe, are designed on the basis of luminance.

The unit of luminance is the candela per square meter (cd/sq.m.). Candelas per square foot is almost never used.

How are Illuminance and Luminance Related?

The amount of luminance on a road surface is dependent upon the lighting falling on the roadway, that is, its illuminance, and the reflectance of the roadway. Different roadway materials have different reflectances. Also, reflectance is not uniform; light reflects more strongly in some directions than others because of varying degrees of glossiness in the surface.

Because many factors influence the level of pavement luminance, there is no simple ratio between average luminance and average illuminance of a roadway. An illuminance of one footcandle (about 10 lux) typically can produce a luminance between 0.3 cd/sq.m. and 0.8 cd/sq.m., depending on lighting geometry, luminaire and lamp type, size, and shape of the lighted area, and the pavement type.