Lumen Effectiveness Multipliers
For
Outdoor Lighting Design

IES Paper no. 50

by

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Introduction

Perhaps one of the most fascinating and important subjects to be addressed in our industry over recent years is the effect of lamp spectral distribution on visibility. In the past, it has been widely accepted that under virtually all circumstances where artificial light is used, lighting level calculations could ignore spectral effects. In IESNA and CIE practice, recommended lighting levels do not consider light source color. When calculating such levels in practical design situations, results are based on a certain lamp lumen rating, usually as provided by the manufacturer. Calculated values of candelas, lux or candelas per sq.m. are not dependent upon whether the light source is bluish white, pink or yellow.

If we review CIE and IES literature, however, it becomes apparent that scientists have known for a long time that light source color is highly important: Light sources of different spectral distributions may produce dramatically different perceived brightnesses even when their luminances (as measured by a traditional meter) are identical. CIE report no. 41, published in 1978, "Light as a True Visual Quantity", gives an example of how an area lighted by a mercury lamp may have double the apparent brightness of that provided by a sodium lamp, for equal luminance.[1]

With regard to vision under low light levels, the CIE report also states "If we use an ordinary light meter, bluish lights will be brighter and more effective for vision than they are given credit for, while yellowish and reddish lights will be over-evaluated for their light-producing capabilities."

The IES acknowledges that there is potential effect of spectral power distribution on visibility.[10] Alman of the National Research Council of Canada in 1977, in an IES Journal paper, reviewed the inadequacies of our present system of photometry.[14] While noting its comparative simplicity, he added the comment "A convenient but incorrect system is no bargain."

Research and publications which indicate the importance of lamp spectral distribution thus have been available for many years. It is only recently, however, that the lighting industry has begun to acknowledge the magnitude of the effects involved, and to show serious interest in correcting the problems. It should also be realized that there may be significant benefits that might accrue from correction of our practices.

The Definition of Light

For reasons which are probably historical, light is defined and evaluated in terms of the visual sensation it produces.[1,2] That, at least, is the aim of our definition of light.

Of all physical qualities, light is unique in that its definition incorporates a human reaction. This is a little like defining a kilogram (or pound) in terms of how heavy an object feels. Imagine the difficulties involved if weight were defined in that way, yet in defining light as we do, we have introduced equivalent difficulties.

The basic definition of light, as described by the CIE and as normally used, is very simple and may be summarized as:

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

K is a constant used to account for units. $V(\lambda)$ is the CIE international standard representing the luminous sensitivity curve of the eye, under certain conditions.[2] The process of determining the lumen output of a lamp therefore is reduced to measuring its power output at close intervals across the visible wavelength and multiplying the power at each wavelength by the applicable $V(\lambda)$ value, and summing the products.

Regrettably, this procedure represents a gross oversimplification of human vision. The $V(\lambda)$ curve was established from research conducted using the fovea, the central 2° ($\pm$ 1°) of the eye’s field of view, and for relatively high (photopic) light levels. If the visual task is off-axis and at a low level of luminance, the $V(\lambda)$ function does not apply. For such conditions therefore, *the fundamental definition of the lumen is misleading at best, and invalid at worst.* If light is to be evaluated in terms of its ability to produce visual sensation, but the method or function used to calculate the quantity of light is inapplicable to the circumstances, then the lumen value so calculated is in error.

Of course, we can say that this is not so, because by definition, $V(\lambda)$ is the function to be used to calculate the lumen, by international acceptance.[2] Therefore if $V(\lambda)$ is used, also by definition, the lumen value so calculated must be correct. Then we must admit, however, that for off-axis low light level conditions, in fact we are *not* evaluating light in terms of the visual sensation it produces.

This difficult situation is acknowledged by the CIE, which has provided considerable detail of the inadequacies of the $V(\lambda)$ curve and the conditions under which its use is inappropriate.[1,3]

A second function, $V'(\lambda)$, is standardized and is useful for describing spectral response of the eye under low light level (scotopic) conditions. This provides a method of calculating scotopic lumens. Unfortunately, under nighttime lighting, the lighting level is rarely, if ever, low enough to be scotopic. Roadway and security lighting almost always lies in the mesopic range, between photopic and scotopic.[4] CIE has not established mesopic response functions for the eye, although the topic has been evaluated at length.[3] Thus it appears that there is a major section of the lighting industry which applies lamp rated lumens under conditions for which they are incorrect. This will underestimate the true performance of some light sources while over-estimating others, perhaps to a major extent.

The important question then becomes; how do we correct this situation? Certainly the (photopic) lumen is well entrenched in every part of lighting literature. It will not go away! Indeed it is a very useful quantity for evaluating light, but should be used only for the conditions to which it applies. What is now needed is a method to extend the principles of photometry and the definition of lighting quantities to other conditions for which lighting design calculations are made.

This paper suggests methods to achieve this goal for consideration by appropriate committees.

Research by Others

The fundamental problem referred to above is not based upon new information. As stated, it has been known for a long time that the V(λ) sensitivity curve of the eye is not applicable at low light levels where the task is off-axis. The information that has dramatized this situation, however, is research that indicates the great magnitude of the effects involved under certain practical situations. Research has shown that changes in visual performance under differing spectral distributions may be vastly greater than, at first examination, can be explained by traditional theory.

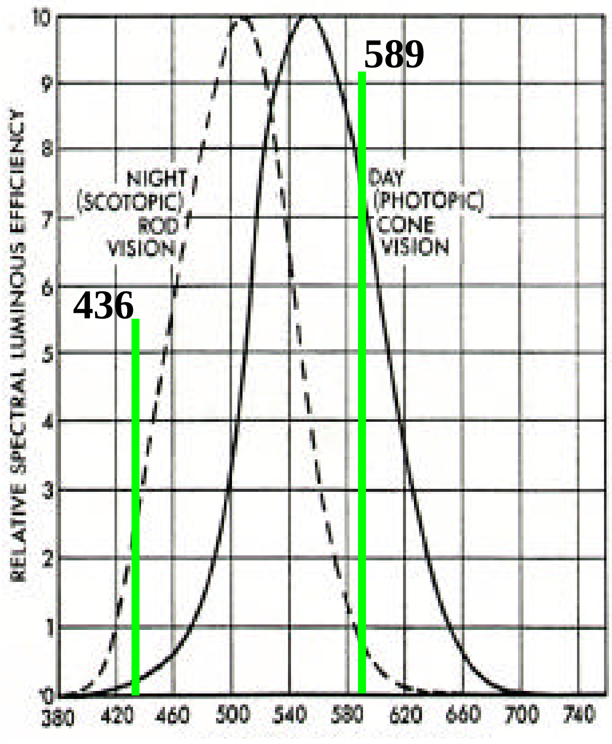

Figure 1. The photopic V(λ) and scotopic V'(λ) eye response curves, with comparisons of spectral lines at 436 and 589 nm.

As light levels reduce from photopic to scotopic levels, the well known Purkinje shift occurs and the peak spectral sensitivity of the eye moves from yellow to blue/green. Figure 1. The photopic response curve is generally taken to be representative of the cone receptors which are densely situated on the axis of the eye and are active under high light levels. The scotopic curve shows the rod response and predominantly applies to the off-axis vision at low light levels. To serve as an illustration, wavelengths of 436nm and 589nm have been highlighted in figure 1. 436nm is the strongest mercury emission line and a powerful line in metal halide lamp output, while 589nm is the region of the maximum output of sodium. The sensitivity of the rods to the mercury line is in fact much greater than is indicated by the standard V(λ) curve. Conversely, the rod sensitivity to the sodium lines is only a fraction of that which V(λ) shows. If rod vision is ignored when we evaluate such wavelengths in calculating lumens, the lumens so calculated are likely to be grossly in error for visual tasks which rely to any extent on rod vision. Such tasks are commonplace at night.

In the mesopic range, roughly .001 cd/sq. m. to 3cd/sq. m., the eye's response for off-axis tasks is between photopic and scotopic. Mesopic response functions have been established, although not standardized, for different levels of mesopic luminances.[3] The situation, however, is enormously complex because the functions are all dependent upon many variables, including the research technique used to derive them. Nevertheless, useful functions have been derived, but these can be used only as a first order approximation. CIE continues in its attempts to develop a comprehensive model of the eye and its response in the mesopic range. (CIE committee 1-37).

Part of this work has been the development of the concept of "equivalent lumens," which seeks to evaluate the light produced by a source under mesopic conditions. The research leading to this concept used experiments primarily involving techniques of brightness matching between sources. Using the functions developed, the equivalent lumens of a source could be determined from the spectral power distribution of the lamp for any level of luminance, including in the mesopic range, but for brightness matching only.

Adrian has computed equivalent lumens for several light sources using these functions rather than the V(λ) curve.[5] Not surprisingly, the lumen quantities computed by this method differ from "normal" lumens under mesopic conditions, (luminances less than 3 cd/sq. m.) As the light level diminishes, yellow sources show a reduction in their output of these equivalent lumens while white sources, or those more heavily dosed with blue and green, show increased equivalent lumens. For example, at low mesopic luminance levels, the output of a metal halide white light source effectively becomes roughly double that of a high pressure sodium source, (on an equal "normal" lumen basis). It should be emphasized that these results are based on brightness matching experiments mainly for tasks occupying both the foveal and off-axis regions of the eye.

Junjian He and his associates have also derived mesopic response functions.[6] However, their work involved tasks situated both on-axis and off-axis, and did not involve brightness matching. Rather, their functions were based on reaction times of subjects under different light sources at different luminances. He's functions are therefore representative of visual performance, not brightness matching, and are therefore of greater significance to the driving task.

Lewis has investigated spectral effects using different methods, also involving visual performance testing of observer reaction times.[7,8] Observers identified the onset of a slightly off-axis potential hazard in a situation intended to simulate driving conditions using different commercially available light sources. Some of Lewis' results are illustrated in figure 2. It will be seen that for a light level of 1 cd/sq. m. for these particular conditions and using a high pressure sodium source, the observer reaction time is approximately 800 milliseconds. To achieve an identical reaction time using a metal halide source, the curves indicate that 0.17 cd/sq. m. is necessary. The ratio of the effectiveness of these two sources is therefore 6:1 for these particular experimental conditions. (1.0/0.17) This is far greater than predicted by Adrian's empirical analysis, or by similar analysis using He's data.

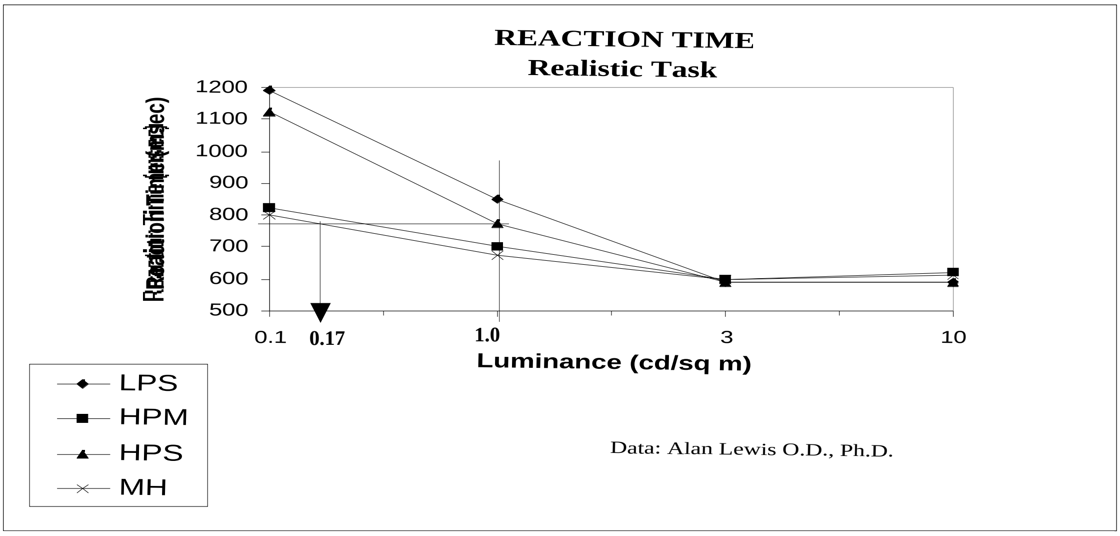

Figure 2. Reaction time data for a realistic task, per Lewis.

Bullough and Rea have conducted experiments which used a driving simulator, where an off-axis task was exposed to observers.[9] The percentage of missed presentations was recorded. They have indicated that a metal halide source can have an effectiveness of 30 times or more than that of a high pressure sodium source, based on identical photopically measured luminance.[9] This result is for an off-axis task at a luminance of 0.1 cd/sq.m.

Clearly there is great diversity in the findings. Empirical data based on the brightness matching mesopic response curves of the eye as used by Adrian do not explain the large apparent benefits attributable to blue/green sources as reported by Lewis and Bullough et al. In addition, there are differences in the results of Lewis versus those of Bullough. The subject appears to be more complex that might first have been suspected.

The explanation for these apparent differences appears to be two-fold. Firstly, the techniques used to establish all of the various eye sensitivity functions described in the CIE report are based either on some form of brightness matching or flicker photometry.[3] The experiments of Lewis, and Bullough et al, however are based on actual measurements of realistic visual performance. The problem is: Brightness matching is not a good predictor of visibility and visual performance. Empirical studies based on data which have been derived from brightness matching, therefore, should not be expected to predict the magnitude of visual performance changes for practical tasks resulting from differences in lamp spectral distribution.

Adrian has provided a correlation of his calculated data with the experimental data of Lewis.[5] What he showed is that the two groups of data assume a generally similar form, but correlation in terms of the magnitude of the effects was not shown. The comparison is discussed in Appendix A.

It is the author's opinion, therefore, that the data and functions summarized in the CIE report[3] are an important indication of certain underlying effects, but that in practical situations involving visual performance of off-axis tasks, they may greatly underestimate the magnitude of the spectral effects.

The differences in experimental results between Lewis and Bullough et al appear to have another explanation: The magnitude of the spectral effects on visual performance is highly dependent upon the nature of the visual task. This is because of several factors:

- If the visual task is on-axis where vision is facilitated by the cones, differences in visual performance at different lighting levels are satisfactorily explained by “normal” photopic lumens.

- At low light levels, the degree to which the visual task is off-axis may affect performance. Not only does the density of rods versus cones increase as the task moves off-axis, but the spatial resolution of the visual system decreases. Visual performance and effects related to spectral distribution therefore are partially dependent upon the task location.

- If an off-axis task, even at low light levels, is easy to perform, perhaps because of high contrast and absence of visual clutter, the visual “signal to noise” ratio is high. Improvements in visual performance due to a more favorable spectral distribution therefore may be only minor. i.e. The task is already easy to see, and it will be seen no matter what spectral conditions apply. Conversely, if a task is difficult and near the threshold of vision, the improvement in visual performance may be very large when the spectral distribution changes from predominately yellow to a blue/green or “pure” white.

- The detection of movement or changing conditions is facilitated best by the rods of the eye, lying in the off-axis field. Tasks incorporating movement or change therefore can be expected to show greater increased benefits from a spectral distribution attuned to the rods, versus static and steady tasks.

For these and other reasons, we should not expect any two different sets of experimental conditions to produce similar results, in terms of how task performance is influenced by lamp spectra. The variables are fundamental and many. Given a particular set of experimental conditions, spectral effects may vary from negligible to major.

Applying the Data in Lighting Design

It is apparent that there is no single number that can be applied in some way to lamp lumens, or any other quantity, which will properly handle all the varying effects of lamp spectral distribution. What appears to be needed is a factor, or series of factors, allowing these effects to be taken into account during the design process to some reasonable and practical extent. We must have a technique which is not unduly burdensome, which is understandable, and which is relatively easy for the designer to incorporate into design calculations. If we do not, it will not be used. (The availability of published research on this subject for 20 years, without it being applied to any significant degree, appears to confirm this thought.)

The author proposes the use of “Lumen Effectiveness Multipliers”, LEM. A value of LEM may be selected by procedures as discussed later, and may be applied in a very simple manner. LEM is a factor to convert the “normal” photopic, or published, lamp lumens to the “effective lumens” for that particular lighting design. The effective lumens more properly will represent some meaningful measure of the visual conditions created.

Effective Lumens = Photopic Lumens x Lumen Effectiveness Multiplier, LEM

Any design calculation based on lamp lumen output can incorporate a chosen value of LEM to increase or decrease the lamp lumen value used. Applying LEM is similar, for example, to Light Loss Factor.[10] Once the LEM value has been selected, the design calculation remains simple and understandable.

Various factors, ratios, indices of merit have been suggested by others.[5,7,8,13] By comparison, LEM has its advantage in fitting directly into everyday design methodology in a way which will be readily understood by lighting designers.

Two points are important:

1. There is no single value of LEM. It must be selected based on applicable conditions, as discussed later. For foveal (on-axis) vision, its value will be 1.0, while for certain peripheral tasks its value may be very large.

2. LEM is a relative value. The V(λ) curve and other similar visibility functions are relative. This is to remove considerable complexities and effects of numerous visual factors which would need consideration if absolute values were used. LEM is most simply defined and used as a ratio of effectiveness between two spectral distributions, for chosen conditions. We may state:

$$\text{LEM} = \frac{\text{Visual effectiveness of the light source}}{\text{Visual effectiveness of a standard light source}}$$

Using a ratio such as this, where the resultant effects are compared to a standard light source, is quite common. For example, Color Rendering Index, CRI, incorporates such a principle.[10] With CRI, the chosen standard light source may be incandescent or daylight.

The future application of LEM, if adopted, will probably be primarily in outdoor lighting, presumably initially in street lighting. By far the most common source in such applications is high pressure sodium, HPS. It is therefore proposed to base LEM on HPS as a standard.

$$LEM = \frac{\textit{Visual effectiveness of the light source}}{\textit{Visual effectiveness of a high pressure sodium source}}$$

In defining LEM in this way, its application becomes even more simple. For lighting designs using high pressure sodium, LEM = 1.0, and no factor needs to be used in the calculations. Suppose a certain light source, perhaps white or blue/green enriched, had been shown by research to have 50% greater effectiveness (under applicable conditions) than HPS. Then for those conditions, LEM = 1.50. The designer can incorporate the factor of 1.50 into the design calculations.

It should be noted that selecting HPS as a reference standard is arbitrary, but appears logical for typical outdoor lighting specifications. In other applications, we may find in the future that use of LEM values is desirable in other situations, perhaps in indoor lighting where different forms of spectral effects have been described.[14,15,16,17] Then a different reference standard may be suitable. With this in mind, perhaps we should designate the above-discussed factor as LEM_1, using a different subscript for possible further LEM values in the future. This is akin to CIE use of Illuminant A, B, C etc. for different standards in color measurement work.

The tricky part of the subject, of course, is choosing what value of LEM is appropriate. It will be dependent upon whether the task is on-axis or off-axis, upon what luminance level is applicable, and upon what is the nature of the visual task, among other factors. Once chosen, however, use of the factor is extremely simple and follows a procedure familiar to all designers.

Selecting the LEM Value

It has been discussed earlier that the effect of a change in lamp spectral distribution is dependent on numerous variables. In addition to considering these variables, we find there are several separate fundamental approaches to developing actual LEM values. We may use, for example:

- Mesopic response functions based primarily on brightness matching data (CIE, Adrian)[3,5]
- Mesopic response functions based on visual performance data. (He)[6]
- Data from visual performance experiments using commercial light sources. (Lewis, Bullough and Rea)[7,8,9]

Use of Mesopic Sensitivity Functions Based on Brightness Matching

The "mesopic lumens" of a source can be calculated by integration, just as photopic lumens are calculated, but using a mesopic response function in place of $V(\lambda)$. All that is needed is the spectral power distribution and a simple computer program. The ratios of mesopic to photopic lumens for the given light source and for the standard reference source, when divided by one another, will then provide the LEM value:

$$\text{LEM} = \frac{\text{Mesopic lumens for source}}{\text{Rated lumens for source}} \times \frac{\text{Rated lumens for HPS}}{\text{Mesopic lumens for HPS}}$$

where HPS = High Pressure Sodium reference source

LEM values for a particular light source at various luminance levels could be provided in tabular form by manufacturers, for use by the lighting designer.

The LEM value derived, of course, will be dependent upon the chosen mesopic response function which is used in place of $V(\lambda)$. Many such functions have been derived by various researchers. Some of these have been described by CIE, and most provide a formula for mesopic response which is based on some combination of photopic and scotopic response functions.[3] Later work has provided a refining of these functions.[12] The nature of the function developed is dependent upon the test conditions used by the various researchers, and none of the functions has been found to be wholly acceptable. They appear, however, to be much superior to simple use of photopic response alone when off-axis vision is important. (See appendix B). All are based to some degree on brightness matching and involve a centrally located task which may also occupy some of the off-axis field.

As described in appendix A, the correlation between this method and visual performance techniques involving off-axis tasks is not good. This is as would be expected. Brightness matching is not necessarily a good predictor of visual performance. Performance is related to many other factors, and changes in performance due to different spectral distributions can be much greater than suggested by mesopic response functions based on brightness matching.[7,8,9]

Use of Mesopic Sensitivity Functions Based on Visual Performance

The mesopic response of functions developed by the He et al do not suffer from the problem of being based on brightness matching data.[6] They are truly a measure of visual performance. The experiments involved the detection of and reaction to both on-axis and off-axis tasks. While He's results suggest that $V(\lambda)$ curve is satisfactory for on-axis tasks, there is a considerable body of evidence to show that off-tasks are very important in the nighttime situation, particularly in driving. Appendix B provides brief information on the relationship of driving safety to the detection of off-axis tasks.

Driving a vehicle involves some combination of on-axis and off-axis tasks. We are uncertain at this time of the relative importance of these two classes of task. Future evidence may strongly indicate that He's off-axis mesopic functions represent the overwhelming visual mechanism contributing to accident avoidance under nighttime conditions.

He's functions can be used in an identical manner to that described for brightness matching functions in developing values for LEM for any spectral distribution. This is a major advantage of this form of research and the data it produces.

Use of Performance Research Data from Commercial Lamp Experiments

Figure 2 has illustrated the perfect simplicity of producing a ratio from performance research results which expresses the effectiveness of one spectral distribution versus another. When HPS is used as the standard, as illustrated by the earlier calculation using figure 2, the resultant calculated value, (6.0 in the example), can be used as a Lumen Effectiveness Multiplier. Data such as shown in figure 2 can be further simplified by being reduced to tabular form. The designer, knowing the luminance level for which he/she is designing could extract the LEM value from such a table and apply it in the calculations.

This method, however, introduces a further set of difficulties: the visual performance changes due to spectral distribution are dependent upon the experimental conditions used to collect the data. The magnitude of performance change will be affected by the nature of the task and the contrast with its background, the task location, relative movement between the task and the observer, and other factors affecting task difficulty. (Note, however, that the same set of problems exists with the use of He's mesopic response functions).

If a standard set of task conditions were to be selected by an appropriate committee, and these conditions were similar to those investigated in a research program, [7,8,9] a series of LEM values for various luminance levels could be developed from the research data. This is a difficult but not necessarily insurmountable task, and is similar to that recently achieved by the IESNA Roadway Lighting Committee in the development of a standard task for Small Target Visibility.[11]

There is a further difficulty: Research data for practical nighttime tasks have been collected using a series of light sources which are presently commercially available.[7,8] No method is currently available to recompute these research results for different spectral distributions which are available now or may be in the future. This is a serious drawback, which is overcome only by the two earlier described methods which can use mesopic eye functions to evaluate any light source once the spectral power distribution is known.

Summary of the Methods of Computing LEM

In summarizing the different methods of developing LEM values, we can state that:

1. Brightness data and mesopic functions derived from such data produce very conservative LEM values, when compared to some published off-axis performance data. This is due to factors such as the inclusion of on-axis effects and the exclusion of movement detection.

   Based on brightness data, white light sources can produce LEM values ranging up to approximately 2, versus values as high as 30 for visual performance tests.[5,7,8,9]

2. Mesopic functions based on brightness matching have been developed and extensively evaluated. While there is no international standard, reasonably good agreement has been found between researchers.[3,12]

3. The mesopic functions so developed are typically for a combination of foveal and off-axis fields. It is not known how well this simulates an outdoor lighting task. Evidence suggests that many accidents may be caused by objects initially detected in the peripheral field. Therefore brightness matching mesopic functions may considerably underestimate the effects of spectral distribution in the practical driving situation.

4. The number of variables involved in visual performance data are a serious drawback to the direct use of research results developed by such methods.

   Before such data can be applied, it appears prudent to have extensive review by appropriate committees, to consider to what extent these data relate to practical nighttime vision. Further analysis of the driving task, in particular, is needed.

5. Direct evaluation of the spectral distribution of new sources requires the use of mesopic response functions, either based on brightness matching or visual performance studies.

It appears, therefore, that there is much known on the subject of mesopic response. Various methods and data sets can be used to develop LEM values for practical use. Of these methods, all have advantages and disadvantages. Use of mesopic response functions appears essential if we are to have the ability to develop LEM tables for any form of light source. LEM values so derived may be quite conservative. However, given the newness of the concept of using such multipliers in lighting design, it may be considered prudent at this time to use conservative values.

As an example to illustrate how the LEM table might appear, table 1 provides LEM values calculated from the work of Adrian and the researchers who contributed to the development of the response functions he used.[5] Because the experimental work involved fields of view which incorporated both the foveal and off-axis fields, they may be considered very conservative if applied in situations occurring where accidents are caused primarily by off-axis objects. The work of He et al[6] and further analysis of He's functions by Rea[13] similarly can be used, and will produce the values provided in table 2. Table 1 is therefore based primarily on brightness matching functions while table 2 is based on mesopic functions derived from visual performance testing.

Direct comparison between the two tables is difficult as different luminance levels were used. Also, there is no guarantee that Adrian, He and Rea used identical spectra for the various sources. In general, however, LEM values for metal halide, at luminances between 0.1 and 3, tend to be higher when brightness matching functions are used. The reverse is true at levels below 0.1 cd/sq.m. The general forms of the data, however, are quite similar.

Table 1
Lumen Effectiveness Multipliers
(High Pressure Sodium = 1.00)
From Brightness Matching Mesopic Functions

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
Clear Mercury	1.48	1.43	1.38	1.22	1.09	1.00
Low Pressure Sodium	0.47	0.51	0.61	0.82	0.95	1.00

Calculated from empirical data developed by Professor W. Adrian. (Ref. 5)

Table 2

Lumen Effectiveness Multipliers
(High Pressure Sodium = 1.00)
From Reaction Time Mesopic Functions

Luminance (cd/sq.m.)	Scotopic	0.03	0.1	0.3	Photopic
Metal Halide	2.58	2.30	1.88	1.40	1.00
High Pressure Sodium	1.00	1.00	1.00	1.00	1.00
Clear Mercury	1.98	1.79	1.53	1.22	1.00
Low Pressure Sodium	0.35	0.46	0.64	0.83	1.00

Calculated from data developed by He et al (ref. 6) and Rea (ref.13).

Higher Light Levels

It will be seen that the values of LEM for high light levels (10 cd/sq. m. and greater) are 1.0 for all sources, based on the research data used to construct the tables.[5,6,13] However, the validity of this has been disputed. Other researchers have found that, in fact, the effectiveness of blue/green enriched sources is greater than that of yellow-rich sources at considerably higher light levels.[14,15,16,17] Evaluation of spectral effects at light levels higher than are typically used for outdoor lighting are not within the scope of this paper. Such evidence, however, is strong and should not be overlooked.

Conclusion

Further work is necessary, particularly in the areas of defining nighttime visual tasks, to determine whether more or larger multipliers can and should be developed to represent additional factors related to visual performance of off-axis tasks.

It is beyond the scope of this paper to recommend actual LEM values which should be used for different sources under different conditions. However, this paper provides an overview of methods and a suggested framework for evaluation by IESNA committees, and example tables of values. Overseas, where this work has been reviewed, rather than a table of LEM's, a value of LEM = 2.0 has been suggested for use when white HID sources are used for roadway lighting design. While this seems to be an oversimplification, the work of Lewis, Bullough et al suggests that different, and perhaps considerably greater, values may be justified in the future for certain types of tasks.

Perhaps we are opening the door to increased nighttime safety and security by developing a methodology to allow the designer to account for light source spectral effects. An associated direct benefit may be a savings in lighting energy. The task of reviewing this work appears potentially worthwhile.

Acknowledgements

The author is greatly indebted to Professor Alan Lewis, Professor Werner Adrian, Professor Mark Rea and Mr. John Bullough for the invaluable input provided in the preparation of this paper.

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Appendix A

Brightness Matching Data versus Visual Performance Data

Adrian computed equivalent luminance, L_{eq}, for various sources at different light levels.[5] L_{eq} expresses the luminance of a source under mesopic conditions, using a chosen mesopic eye response function. A "figure of merit" was provided, which is the ratio of L_{eq}/L, where L is the luminance calculated using the photopic response curve. As the light level reduces, the figure of merit increases for white or blue-rich sources and decreases for yellow-biased sources. The values of L_{eq} are based primarily on data from brightness matching experiments. It has been claimed that computed L_{eq} values satisfactorily explain the differences in visual performance found under different light sources by Lewis.[7,8] On closer examination, this appears not to be so, as the effects Lewis reported are much greater than are predicted by the mesopic response functions.

Data presented in table 1 of reference 5 show good agreement between Lewis' Contrast Sensitivity values and the L_{eq}/L figure of merit for metal halide lamps. It was therefore apparently concluded that the L_{eq} values can be used as a basis of developing a comparison of lumens needed to produce a certain level of visual performance, table 4 of reference 5. However, when low pressure sodium data is compared, table 2 of reference 5, the figure of merit is grossly different from the experimentally developed Contrast Sensitivity values. The figure of merit for LPS at 0.1 cd/sq.m. is 63% below unity, while the Contrast Sensitivity data shows a value of only 16%. Table 4 of reference 5 nevertheless uses the figures of merit to develop data on lumens for equal visual performance.

Figure 2 of this present paper provides data from Lewis for a realistic reaction time test.[8] From this data, it can be seen that a luminance level of 1 cd/sq.m. produces approximately an 800 msec reaction time for high pressure sodium lighting, for these experimental conditions. The required luminance for metal halide lighting is 0.17 cd/sq.m. Thus metal halide is shown to be 6 times more effective than HPS in this experiment. However, in reviewing reference 5, table 4, the relative lumens of HPS at 1 cd/sq.m. are shown as 126. The relative lumens for metal halide at 0.17 cd/sq.m., by interpolation, are 91, for the same visual performance. Thus according to, table 4 of reference 5, the ratio of effectiveness of metal halide versus HPS on an equal lumen basis is only 126/91, or 1.38, not the value of 6 shown by Lewis.

Data presented graphically in figure 17 of reference 5 show similar trends for the figure of merit (left Y ordinate) and ratio of speed (right Y ordinate). However, had different scales been chosen for the two ordinates, it would be apparent that there is no correlation in absolute magnitude of the results between the empirical (reference 5) and visual performance data (reference 7). All that can be claimed is that similar trends exist.

Appendix B

Foveal versus Peripheral Vision

Let us consider certain factors involved in night driving and how they may relate to LEM.

When a driver is looking straight ahead, the task is on-axis and eye behavior can be characterized by photopic conditions. For this over-simplified situation, LEM = 1.0.

We must realize, however, that accidents usually are caused when the eye does not detect the hazard. This is most likely to happen when the task is difficult to see, as in the case of objects which appear in the peripheral field, where the light level is usually lower than on the roadway itself. This emphasizes the importance of any effects created by the lighting for low luminance tasks which are initially seen off-axis.

Further, accidents involve some form of relative motion between the driver and the hazard. Two objects cannot strike each other unless relative motion occurs. Because the peripheral field of the eye is particularly sensitive to such motion, improvement of visibility in the periphery is likely to have a great effect on accident reduction.

The study of the effects of lamp spectra, applicable as they are to off-axis mesopic vision, therefore relates directly to the perception of precisely those tasks which are a major cause of accidents. A child running towards the roadway in the relative darkness, or another vehicle approaching from a side street, are examples of low luminance off-axis tasks. Bullough and Rea have reported data which compute to LEM values of 30 or more for off-axis tasks! It is recognized that the driver will frequently turn his attention to the off-axis task by directing his eyes towards it. The point is, however, that *initial detection of such hazards is accomplished by off-axis vision.*

There are many references in published literature to show that driving and accident avoidance are highly reliant upon peripheral vision.[B1,B2,B3] The argument that on-axis vision is unaffected by spectral effects, and therefore they may be ignored, simply is not borne out by practical experience or research. Imagine driving with a cardboard tube in front of each eye. If the tubes are 4.4 cm (1.75 inches) in diameter and 127 cm (50 inches) long, they will accept all on-axis vision while eliminating peripheral vision. Figure B1. It is intuitively obvious that driving under such conditions would create a dangerous and alarming situation. The visual input derived from our peripheral field while driving is enormous. Unfortunately, however, we do not yet have full information on the relative importance of off-axis tasks versus on-axis tasks for nighttime situations. This work must be undertaken.

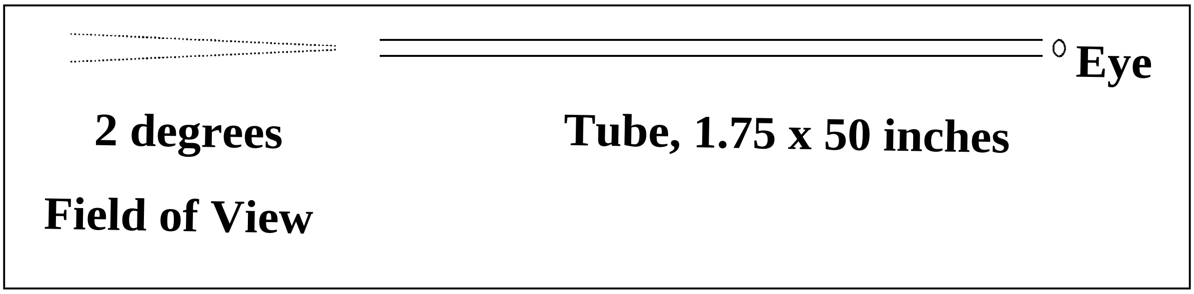

Figure B1. Viewing through a tube to simulate the on-axis foveal field.

References for Appendix B

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