A Mesopic Vision Approach for a Better Design of Road Lighting

N. BISKETZIS G. POLYMEROPOULOS F. V. TOPALIS
School of Electrical and Computer Engineering
National Technical University of Athens
9 Iroon Politechniou St., 15780 Athens
GREECE
Tel: +30-2107723627, Fax: +30-2107723628

Abstract: This paper approaches the design of road lighting from the point of view of mesopic vision. Up to date all lighting calculations are performed for photopic visual conditions. Although this is true for interior lighting, it is not always the case for road lighting. Usually, the luminance level on roads of low or medium traffic, fall below the lower limits of photopic vision. In that case, the vision becomes mesopic. Recent researches have proved that in mesopic visual conditions the sensitivity of the human eye moves to lower wavelengths. Therefore, some types of lamps which are widely used for road illumination (e.g. high-pressure sodium) are not as efficient as they use to be in the photopic vision. It seems that the efficiency of lighting installations could be improved by using lamps with light spectrum richer in shorter wavelengths (e.g. metal halide). This paper shows that the road lighting quality parameters may be improved if the high-pressure sodium lamps are replaced by metal halide lamps in identical lighting installations, given that the visual performance of the eye is considered under mesopic vision. The calculations shown in this paper prove that metal halide lamps are more efficient than is usually believed and, moreover, energy savings could be achieved.

Key-words: mesopic vision, road lighting, high intensity discharge lamps.

1 Introduction

It is well known that the maximum spectral sensitivity of the human eye shifts towards smaller light wavelengths when the luminance decreases (Purkinje shift). Obviously, the light gets dimmer when the luminance decreases. In that case the light appears to be less bright than the photopically calculated if the lamp (e.g. high-pressure sodium) is rich in long wavelengths (Fig.1). On the contrary, if the light source is rich in short wavelengths (e.g. metal halide lamp), then the light appears to be brighter than the calculated one (Fig.2).

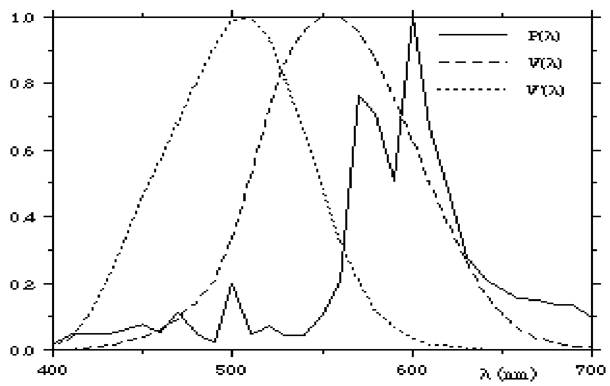

Fig. 1. Spectral power distribution of high pressure sodium lamps

The human's eye response depends on many factors. One of the most important is the luminance level. The human vision can be divided in two main ranges according to the luminance levels: the photopic range (luminance above 10cd/m^2) and the scotopic one (luminance below 10^{-3}cd/m^2). The vision in the intermediate region is called mesopic. Different spectral luminous efficiency functions of the human eye characterize each range. Especially mesopic vision is characterized by a family of spectral luminous efficiency functions, one for each luminance level. Obviously the luminous flux of a lamp will be different in each region of vision.

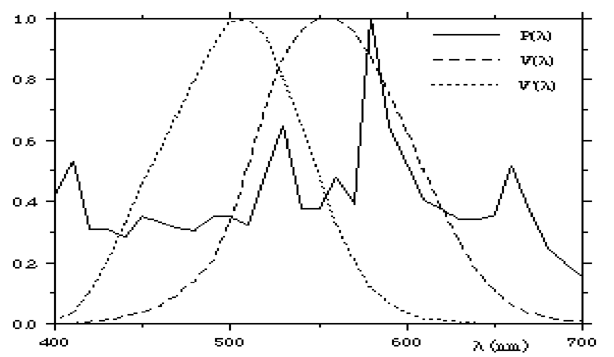

Fig. 2. Spectral power distribution of metal halide lamps.

Luminance, in several outdoor lighting applications, is within the mesopic range. Road lighting is a typical case. Therefore, it is of great importance to calculate the luminous flux of each type of lamp at every luminance level.

The determination of the mesopic curves was not feasible until know because of the complexity of the mesopic vision. On the other hand, many techniques have been developed in order to determine the lighting equivalence among the different types of lamps, for various luminance levels. The use of a matching criterion is common in these techniques. The criterion could be purely optical as the brightness matching or a complicate one, as the reaction time. The experimental results from these techniques do not converge. As expected, the results depend on many factors such as the experimental apparatus, the matching criterion and many others. It is obvious that for road lighting applications the most suitable criterion is reaction times.

In this paper the results from two types of models are examined for the mesopic vision, which are based on brightness matching and the reaction time. Moreover, these models are applied to compare the performance of the commercially available types of lamps in the lighting of three typical roads. The objective is to determine the equivalent luminance with each type of lamps in order to have equal reaction times from a typical driver.

This application shows that the luminous efficacy of the lamps in the mesopic range is significantly different from the efficacy in the photopic range. In other words, the nominal flux of lamps is not valid in the mesopic range. Thus, if the results from the mesopic vision research are taken into account, some benefits will be achieved: safety at night driving, energy saving and less light pollution.

2 Mesopic Visual Performance

Many papers have been published on the visual performance of the human eye within the mesopic range. They approach this matter using two main views. One considers the brightness matching as the visual performance. The other considers the reaction time.

2.1 Brightness matching

Brightness matching is the requirement for the radiance of the tested light source to match the apparent visual brightness of the reference light source [1]. As already mentioned, two light sources having equal brightness within the mesopic range, do not necessarily produce equal photopic luminances. The most important researches have been carried out by Palmer (two models), Kokoschka, Ikeda and Sagawa. They investigated the brightness matching throughout the mesopic range of diverse light sources. Finally they constructed five mathematical models providing the mesopic equivalent luminance of any light source of known spectral distribution.

The mesopic luminance values from commercially available high-pressure sodium (HPS) and metal halide (MH) lamps are shown in Tables 1, 2 and 3. These values are derived from the above five models [2] for various luminance levels. It seems that there are no essential differences between the models. However, no one of them has been fully approved.

Table 1. Calculated mesopic luminance from HPS and MH lamps in the order of 1cd/m^2.

Luminance (cd/m^2)	HPS	MH
Scotopic	0.68	1.63
Photopic	1.03	0.93
Palmer 1st formula	1.02	0.99
Palmer 2nd formula	1.04	0.97
Kokoschka	1.02	1.02
Ikeda	1.04	0.97
Sagawa	0.99	0.93

Table 2. Calculated mesopic luminance from HPS and MH lamps in the order of 0.1cd/m^2.

Luminance (cd/m^2)	HPS	MH
Scotopic	0.076	0.161
Photopic	0.114	0.092
Palmer 1st formula	0.105	0.115
Palmer 2nd formula	0.104	0.112
Kokoschka	0.106	0.116
Ikeda	0.112	0.100
Sagawa	0.094	0.116

Table 3. Calculated mesopic luminance from HPS and MH lamps in the order of 0.01cd/m^2.

Luminance (cd/m^2)	HPS	MH
Scotopic	0.0094	0.0147
Photopic	0.0142	0.0084
Palmer 1st formula	0.0107	0.0136
Palmer 2nd formula	0.0116	0.0118
Kokoschka	0.0109	0.0118
Ikeda	0.0118	0.0119
Sagawa	0.0102	0.0129

2.2 Reaction time

Reaction time is the time needed for a subject to react to specific stimulus, when the luminance level is in the mesopic range. Lewis, He, Bullock & Rea have made researches on this subject, but their results do not agree well due to different reasons.

Lewis investigated the visual performance under lighting conditions created by four lamp types with different spectral power distributions: high pressure sodium, low pressure sodium, high pressure mercury, incandescent and metal halide.

The measurements have been carried out using five young male observers aged 20-25 years. The reaction time to a stimulus at gaze slightly off-axis has been measured at luminance levels in the range of 0.1-10.0cd/m^2. The experiments showed that the reaction times were essentially equal at photopic luminances irrespective of the source. However the reaction times at luminances below 1.0cd/m^2 were lower with sources radiating more power at short wavelengths. As reference is taken the reaction time with an MH lamp at the luminance levels 0.1 and 1.0cd/m^2. Table 4 shows how effective is the luminance from each light source i.e. how many times should be multiplied the luminance from a specific light source in order exhibit equal reaction time to the reference one with the MH lamp [3].

Table 4. Luminance multiplier for equal reaction time between a light source and the MH lamp.

Lamp	Luminance multiplier	
	0.1cd/m^2	1.0cd/m^2
Metal halide (reference)	1.0	1.0
Incandescent	2.9	1.5
High pressure mercury	4.4	2.4
High pressure sodium	7.8	3.9
Low pressure sodium	14.6	4.8

He, Rea, Bierman and Bullough used two light sources (HPS and MH lamps) for eight background luminances (0.003–10cd/m^2) and two target locations (on-axis and off-axis). Three young observers were used in the age of 28-31 years. They concluded that their on-axis reaction times were independent from the light source. On the other hand, their off-axis reaction times showed a significant difference only below 0.6cd/m^2 [4].

Table 5 shows how many times lower the required luminance from an MH lamp is, in order to exhibit the same reaction time with an HPS lamp. It should be noticed that the MH lamps become more efficient than the HPS lamps at lower mesopic luminance levels.

Bullough and Rea have carried out experiments using a driving simulator. An off-axis task was exposed to subjects. The percentage of missed presentations was recorded. It was deduced that an HPS lamp was 30 times less effective than the MH at the same photopic luminance of 0.1cd/m^2 [5].

Table 5. Photopic luminance ratio for equal reaction times between MH and HPS lamps.

L_{HPS} cd/m^2	L_{HPS}:L_{MH}
10.00	1.000
3.00	1.000
1.00	1.000
0.30	1.395
0.10	1.910
0.03	2.365
0.01	2.685

It is concluded from the above mentioned investigations that there is a remarkable diversion between their results. Therefore the research on the reaction time within the mesopic range is far from final yet. Nevertheless, it can be said that He's results are more mediocre than Lewis', while Rea's are the most exaggerated of all. The road lighting applications of this paper follow the methodology of Lewis.

3 Mesopic Vision in Road Lighting

3.1 Methodology

Road lighting is the main application field of mesopic vision research. In this case the desired luminance usually falls within the mesopic range. The required levels of luminance for road lighting in several countries are summarized in Table 6. In all cases the highest values are applied to high-speed roads with separate carriageways (motorways, highways). The lowest values apply to less important, low traffic, roads.

Three urban roads of low and medium traffic are examined in this paper. The required average luminance for all of them is below 1.5cd/m^2 according to CIE 132 (1999) [6] that is applied.

First, the road lighting parameters are calculated using HPS lamps (Philips SON-TP). Then the HPS lamps are replaced by MH ones (Philips CDM-T). The lighting installation remains exactly the same (road width, pole height and spacing) as well as the luminaire that is suitable for both HPS and MH lamps (Philips SGS 203 & 253 PC P3). The only component that changes is the lamp. Therefore the two lighting installations differ only in the lamp. Finally, the calculated results are compared in terms of reaction time using Lewis' methodology and in terms of brightness matching using Palmer 1st formula.

Table 6. Luminance limits for road lighting.

Country	L_{av}	L_{min}/L_{max}	L_{min}/L_{av}
CIE	2.00-0.30		0.35
Belgium	2.00-0.30		0.35
France	2.00-0.50		0.40
Germany	2.00-0.50	0.77-0.50	
Italy	2.00-0.50		0.40-0.35
Switzerland	2.00-0.50	0.40	

3.2 District distributor road

The road of the first application is a typical single carriageway urban road of 6m in width. It consists of 2 lanes. The lighting installation is single sided right. The height of the poles is 7m and the spacing is 28m. The road it is categorized to the M3 lighting class according to CIE 132 (1999) [6]. The data of this application are summarized in Table 7.

Table 7. District distributor road data.

w=6m	h=7.0m	s=28.0m
High pressure sodium (HPS)		
SGS 203 PC P3	1× SON–TP 70 W	
Lamp flux	6600 lm	
Luminaire wattage	80 W	
Metal halide (MH)		
SGS 203 PC P3	1×CDM-T 70W/830	
Lamp flux	6600 lm	
Luminaire wattage	83 W	

The calculations are performed following the requirements for roads of M3 class, which are the following:

$$L_{av} \geq 1cd/m^2 \text{ and } L_{min}/L_{av} \geq 0.40$$

It can be observed in Table 8 that both systems give the same average photopic luminance. However, the road is slightly brighter with the MH lamp. On the other hand, the MH lamp produces better reaction time than the HPS lamp, although the luminous flux and the wattage of the lamps are equal.

It is also noticeable that the MH system performs better than the HPS one in terms of reaction time at the areas with the minimum photopic luminance. (Table 9). Regarding the apparent brightness, the HPS system is better.

Table 8. Reaction time and brightness matching (mesopic luminance) for equal average photopic luminance.

Lamp	L_{av} cd/m^2	Apparent brightness cd/m^2	Reaction time ms
HPS	1.02	1.01	754
MH	1.02	1.03	660

Table 9. Reaction time and brightness matching (mesopic luminance) vs. the minimum photopic luminance.

Lamp	L_{min} cd/m^2	Apparent brightness cd/m^2	Reaction time ms
HPS	0.62	0.61	835
MH	0.36	0.41	723

The photopic luminance uniformity (L_{min}/L_{av}) is much better with the HPS lamps (Table 10). In that case the uniformity with the MH system is below the lower accepted value (0.36<0.40). The mesopic luminance (brightness) uniformity is also better with the HPS system although the difference is smaller. In that case the mesopic uniformity of the MH system is within the limits (0.40).

Table 10. Photopic and mesopic uniformity.

Lamp	L_{min}/L_{av} photopic	L_{min}/L_{av} mesopic
HPS	0.61	0.60
MH	0.36	0.40

It is more than obvious that in spite of the lower photopic luminance with the MH lamps, the reaction times are always better for both average and minimum luminance (Tables 8 and 9). However, the apparent brightness with the MH lamps (calculated using Palmer 1st formula) is lower at the areas of the minimum luminance (Table 9). Generally, the uniformity with the MH system is poor as compared to the uniformity with the HPS system (Table 10) that is better and within the limits.

3.3 Residential major access road

The road of the second application is a typical single carriageway urban road of 7.5m in width. It consists of 3 lanes. The lighting installation is single sided right. The height of the poles is 6m and the spacing is 30m. The road it is categorized to the M4 lighting class according to CIE 132 (1999). The data of this application are summarized in Table 11. Since it is a medium traffic road, the following CIE limits are applied:

$$L_{av} \geq 0.75cd/m^2 \text{ and } L_{min}/L_{av} \geq 0.40$$

Table 11. Residential major access road data.

w=7.5m	h=6m	s=30m
High pressure sodium (HPS)		
SGS 253 PC P3	1× SON–TP 70 W	
Lamp flux	6600 lm	
Luminaire wattage	80 W	
Metal halide (MH)		
SGS 253 PC P3	1×CDM-TT 70W/830	
Lamp flux	6600 lm	
Luminaire wattage	83 W	

The average apparent brightness is better, when HPS lamps are used (Tables 12 and 13) However, the difference in brightness between HPS and MH lamps is less than the photopically calculated. It is noticeable that the photopically calculated average luminance with MH lamps is not acceptable ($0.69<0.75cd/m^2$). On the contrary, the mesopic brightness is acceptable ($0.75cd/m^2$).

The uniformity L_{min}/L_{av} is better with the MH system than with HPS. The uniformity becomes better, when apparent brightness is taken into account (Table 14).

Table 12. Reaction time and brightness matching (mesopic luminance) vs. the average photopic luminance.

Lamp	L_{av} cd/m^2	Apparent brightness cd/m^2	Reaction time ms
HPS	0.80	0.79	795
MH	0.69	0.75	683

Table 13. Reaction time and brightness matching (mesopic luminance) vs. the minimum photopic luminance.

Lamp	L_{min} cd/m^2	Apparent brightness cd/m^2	Reaction time ms
HPS	0.35	0.34	930
MH	0.31	0.36	732

Table 14. Photopic and mesopic uniformity.

Lamp	L_{min}/L_{av} photopic	L_{min}/L_{av} mesopic
HPS	0.43	0.43
MH	0.45	0.48

3.4 Local distributor road

The road of the third application is a typical single carriageway secondary urban road of 6m in width. It consists of 2 lanes. The lighting installation is staggered. The height of the poles is 6m and the spacing is 34.5m. The data of this application are summarized in Table 15. The road is categorized to the M5 lighting class according to CIE 132 (1999). Since it is a low traffic road, the following CIE limits are applied.

$$L_{av} \geq 0.5cd/m^2 \text{ and } L_{min}/L_{av} \geq 0.35$$

In this case the MH lamps always produce better reaction times than HPS lamps (Tables 16 and 17).

Table 15. Local distributor road data.

w=6m	h=6m	s=34.5m
High pressure sodium (HPS)		
SGS 253 PC P3	1× SON–TP 70 W	
Lamp flux	6600 lm	
Luminaire wattage	80 W	
Metal halide (MH)		
SGS 253 PC P3	1×CDM-TT 70W/830	
Lamp flux	6600 lm	
Luminaire wattage	83 W	

Table 16. Reaction time and brightness matching (mesopic luminance) vs. the average photopic luminance.

Lamp	L_{av} cd/m^2	Apparent brightness cd/m^2	Reaction time (ms)
HPS	0.66	0.65	825
MH	0.56	0.62	695

Table 17. Reaction time and brightness matching (mesopic luminance) vs. the minimum photopic luminance.

Lamp	L_{av} cd/m^2	Apparent brightness cd/m^2	Reaction time (ms)
HPS	0.23	0.22	999
MH	0.18	0.22	765

The photopically calculated value of average luminance with MH lamps is acceptable ($0.56>0.50$ cd/m^2). However the apparent brightness is less than the one with HPS, although their difference is smaller ($0.65–0.62cd/m^2<0.66–0.56cd/m^2$).

The photopically calculated uniformity L_{min}/L_{av} with HPS is better than that with MH (Table 18). However this relation is reversed when mesopic calculations are used. In this case, the mesopically calculated uniformity with HPS is not acceptable.

Table 18 Photopic and mesopic uniformity.

Lamp	L_{min}/L_{av} photopic	L_{min}/L_{av} mesopic
HPS	0.35	0.34
MH	0.32	0.35

4 Discussion

As it has been already mentioned, two main methods were used for the mesopic vision research. These methods are based on two different matching criteria: brightness matching and reaction time.

The disagreement between the experimental results from these two methods is remarkable. This is due to the fact that the reaction time depends not only on the brightness of the target but to several other human factors. This is obvious in photopic vision where excessively high luminances do not produce smaller reaction times.

Also, there are differences among the results from researches using the same matching criteria. Probably, this is due to the fact that the above mentioned researches have not used lamps with the same spectral distributions or with the same angle of vision.

In case of road lighting, the reaction time is of great importance. This the most important factor for the prevention of accidents. Important factor for driving is not only the central 2^o-width on-axis vision but the peripheral vision as well. The sidewalk and any obstacle at the side end of the street are detected by the peripheral vision.

The analysis of the optical properties of this paper has been made only for two lamp types: the HPS and the MH ones. However, it has not been made an analysis of the economical figures in order to examine whether is profitable the substitution of HPS lamps by MH ones. It should be stressed that the lifetime of MH lamps is 8000 hours, but the average lifetime of HPS is 15000 hours.

5 Conclusion

In the low luminosities, i.e. in streets of small and medium traffic, it is possible to replace the already existing HPS lamps of the lighting installations with MH lamps.

Regarding to apparent brightness and uniformity, the HPS lamps give higher values than the MH ones. Occasionally however, the photopically calculated values with MH lamps may be slightly below the limits while the mesopically calculated values fall within the limits. The mesopic uniformity ratio at low luminances with HPS may be proved not acceptable while the photopic value appears within the limits.

Regarding to the reaction time for slightly off-axis vision, it is always less with MH lamps. It is true that the reaction time is of great importance for the prevention of driving accidents.

References:

[1] Commission Internationale de l' Eclairage, "*Light as a true visual quantity-Principles of measurement*", Publication No. 41, 1978.

[2] Commission Internationale de l' Eclairage, "*Mesopic photometry. History, special problems and practical solutions*", Publication No. 81, 1989.

[3] A. Lewis, "Equating light sources for visual performances at low luminances", *Journal of the Illuminating Engineering Society of North America*, Vol. 27, No. 1, 1998.

[4] Y. He, M.S. Rea, A. Bierman, J. Bullough, "Evaluating light source efficacy under mesopic conditions using reaction time", *Journal of the Illuminating Engineering Society of North America*, Vol. 26, No.1, 1997.

[5] J. Bullough, M.S. Rea, "Simulated driving performance and peripheral detection at mesopic light levels", *International Journal of Lighting Research and Technology*, Vol. 32, No 4, 2000.

[6] Commission Internationale de l' Eclairage, "*Design methods for lighting of roads*", Publication No. 132, 1999.