STUDIES ON LUMINANCE FOR ROAD LIGHTING DESIGN IN MESOPIC DIMENSIONING

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THE REQUIREMENTS FOR DEGREE OF

MASTER OF TECHNOLOGY
ILLUMINATION TECH & DESIGN

SUBMITTED BY

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RECOMMENDATION CERTIFICATE

This is to certify that the thesis entitled "STUDIES ON LUMINANCE FOR ROAD LIGHTING DESIGN IN MESOPIC DIMENSIONING" submitted by BARNALI MONDAL JANA (Examination Roll No:M6ILT22003, Registration No.150170 of 2019-2020) of this university in partial fulfilment of requirements for the award of degree of M.Tech in Illumination Tech &Design, School of Illumination Science, Engineering & Design, is a bonafide record of the work carried out by her under my guidance and supervision.

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This foregoing thesis is hereby approved as a creditable study in the area of Illumination Engineering, carried out and presented by BARNALI MONDAL JANA, in a manner of satisfactory warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is notified to be understood that by this approval, the undersigned do not necessarily endorse or approved the thesis only for the purpose for which it has been submitted.

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ABSTRACT

Mesopic photometry region (i.e. luminance between 0.005 cd/m^2 and 5cd/m^2) lies between scotopic and photopic regions. Luminance level in most of the road lighting and outdoor lighting installations lies in the mesopic zone. Significant work has been done in this regard for road lighting applications, but outdoor lighting is comparatively untouched. In mesopic photometry, adaptation luminance is needed to derive the Mesopic luminance for the measurement field. The average luminance of the visual adaptation field is considered as the adaptation luminance. This work tries to get formulate a mathematical model such that from the lamp characteristics alone (IES file), the photopic , mesopic and adaptation luminance can be calculated without any experimental set up using MATLAB software .

CHAPTER 1:

INTRODUCTION

The International Commission on Illumination (CIE) has recommended a mesopic photometry system based on peripheral visual performance of tasks within the range of 0.005 cd/m2 to 5 cd/m2 and a combination of photopic vision and scotopic vision. Most night-time outdoor and traffic lighting scenarios are in the mesopic range.

Humans see differently at different light levels. This is because under high light levels typical during the day (photopic vision), the eye uses cones to process light. Under very low light levels, corresponding to moonless nights without electric lighting (scotopic vision), the eye uses rods to process light. At many night-time levels, a combination of both cones and rods supports vision. Photopic vision facilitates excellent colour discrimination ability, whereas colours are not discriminable under scotopic vision. Mesopic vision falls between these two extremes. In most night-time environments, there is enough ambient light at night to prevent true scotopic vision. Mesopic photometry aims to measure light in a way which correlates with the mesopic vision. In mesopic photometry, adaptation luminance is needed to derive the Mesopic luminance for the measurement field. Adaptation luminance is the average luminance (or brightness) of those objects and surfaces in the immediate vicinity of an observer estimating the visual range. The adaptation luminance has a marked influence on an observer's estimate of the visual range because, along with the visual angle of the object under observation, it determines the observer's threshold contrast. High adaptation luminance tends to produce a high threshold contrast, thus reducing the estimated visual range. This effect of the adaptation luminance is to be distinguished from the influence of background luminance.

Main objective of the thesis is to measure the performance for different lamps in outdoor lighting scenario under Mesopic luminance range and to measure and compare adaptation luminance for all relevant S/P ratio (i.e. Scotopic/Photopic ratio) of lamps in Matlab after formulated a mathematical modelling such that only IS file of different luminaire will be sufficient to calculate photopic ,mesopic and adaptation luminance without experimental setup.

Therefore, the photopic luminance and vertical illuminance have been measured under different lamp and adaptation conditions. Then after the determination of S/P ratios, CCT & SPD of the lamps, Mesopic Luminances are calculated and Adaptation Luminances are simulated using MATLAB software. After that from the obtained results Lp, Lmes, and La of different lamps are compared under different surrounding luminance conditions.

1.1 Literature Survey

- *Roman Dubnièka, DionýzGašparovský , "Classification system for lighting design under condition of mesopic photometry". 2016 IEEE Lighting Conference of the Visegrad Countries*

  From this paper it is understood that amount of adaptation luminance which is equired for the computation or determination of the mesopic photometric quantity for example luminance or illuminance in mesopic photometry system. This is mainly dependent on visual field of observer and also value of this photometric quantity is different for various situations in scene of the visual field of observer. The paper deals with various situations which occur on the road under public lighting to analyze of possibility of assessment of adaptation luminance. The results can be used for creation of appropriate classification system for practice and lighting designer to allow calculation of the photometric

- *M Maksimainen, M Puolakka, E Tetri and L Halonen, "Veiling luminance and visual adaptation field in mesopic photometry". Lighting Res. Technol. 2017; vol.49 ;743 - 762*

  This paper states that, in mesopic photometry, adaptation luminance is needed to derive the Mesopic luminance for the measurement field. The average luminance of the visual adaptation field is considered as the adaptation luminance. The visual adaptation field has yet to be defined in terms of the size, shape, or location within the visual field. A study in three road lighting situations was conducted, in order to determine the practicability of using the road surface as the adaptation field compared to circular or elliptical adaptation fields. Currently, the road surface is used as the measurement field for calculating road lighting. Using the road surface as the adaptation field resulted in 76–113%, higher average luminance than obtained using circular or elliptical adaptation fields when the road was bordered by a park. High luminance sources outside of the visual adaptation field cause veiling luminance. Veiling luminance increases the adaptation state, but not the luminance within the measurement field. The bias veiling luminance can cause on mesopic luminance calculations was estimated to be less than 2%. The estimated bias can be considered negligible in practical road lighting measurements.

- *T Uchida, M Ayama, Y Akashi, N Hara, T Kitano, Y Kodaira, K Sakai, "Adaptation luminance simulation for CIE mesopic photometry system implementation". Lighting Res. Technol.2016 ;vol.48 ; 14-25*

  This paper described a simulation method to determine adaptation luminance is proposed for implementation of the CIE mesopic photometry system. The simulation takes four factors into account: luminance distribution, eye movement of observers, surrounding luminance effect and area of measurement. Each factor is modelled as a two-dimensional geometrical function. The method determines an adaptation luminance for the area of measurement through four calculation steps. The simulation method was applied to examples of luminance distributions of outdoor lit scenes and the results were compared with possible simple predictors of adaptation luminance. The comparisons suggest that the average luminance of the area of measurement can be considered as a good approximation in most of the cases. Exceptions are scenes for pedestrians in which there are many bright sources surrounding the area of measurement.

- *T Uchida, YOhno, "Simplified field measurement methods for CIE mesopic Photometry System". Lighting Res. Technol .2017 ; vol.49. ;774- 787*

  This paper discussed that, for implementation of the mesopic photometry system in CIE 191:2010 to outdoor lighting, two simplified methods to measure the mesopic luminance are proposed. One of the methods, named the Adaptation Spectral Power Distribution method, assumes that the spectral power distributions (SPDs) of reflected light at test points on the road surface are the same as that of the adaptation field. Another method, named the Source SPD method, assumes that the reflected light SPDs are equal to the SPD of the light source. Error simulations with a real road surface spectral reflectance dataset show that the error distributes over an 8% range due to the variation of the road surface spectral reflectance in the worst case. Although the bias due to the road surface spectral reflectance causes a large error with the Source SPD method, a proposed correction can reduce the error sufficiently. Error simulations also show that the Source SPD method is not so sensitive for lighting scenes that include multiple light source types. It has been shown that the SPD methods can measure the mesopic quantities without scotopic/photopic luminance meters having both $V(\lambda)$ and $V'(\lambda)$ detectors when both the adaptation field and test points consist of road surfaces.

- *T Uchida, Y Ohno, "Defining the visual adaptation field for mesopic photometry: Effect of surrounding source position on peripheral adaptation". Lighting Res. Technol .2017 ; vol.49 ; 763 -773*

  This paper states that, in CIE 191:2010, the Commission International de l'Eclairage recommends a mesopic photometry system based on peripheral visual tasks. For implementation of the system, the visual adaptation field needs to be defined, taking into account the surrounding luminance effect on the state of adaptation. A series of vision experiments in the mesopic range has been conducted to measure the surrounding luminance effect with respect to the angle between a peripheral task point and a point source. The results show that the surrounding luminance effect at a peripheral task point decreases with increasing angle at a larger slope than existing models, such as the Stiles-Holladay equation, the Commission Internationale de l'Eclairage general disability glare formula and the Stiles– Crawford equation. A new model for the surrounding luminance effect is proposed.

- *Efficiency in Street Lighting Projects by Employing LED Luminaires and Mesopic Photometry: Cristiano Casagrande; Fernando Nogueira; Marlon Salmento; Henrique Braga,* ***Published in:*** *IEEE Latin America Transactions (volume: 17, Issue: 06, June 2019)*

  This paper discusses the importance of adapting conventional photometric quantities when lighting systems with low luminance levels are under analysis, as public lighting or external lighting in general. In this sense, it is presented an alternative methodology for lighting projects in street lighting, considering the mesopic photometry. The CIE recommendation 191:2010 proposes correction factors that convert conventional photometric quantities (photopic) into quantities adapted to the corresponding mesopic level. However, a necessary parameter to obtain these correction factors is the relationship between the scotopic and photopic light fluxes of a light source (S/P ratio), which requires special equipment that it is not easily available to engineers, technicians and lighting designers. Thus, this paper proposes a general equation that provides the S/P ratio as a function of the correlative color temperature and the color rendering index of the light source, which are information provided in the manufacturers' catalogs or electric lamp packages. To illustrate the application of the experimentally derived relationship, a typical street lighting project is considered, specifically a retrofit from HPS lamps to modern LED luminaires. In this case, the conventional routine must be changed, allowing the adaptation of conventional quantities to mesopic quantities without need for specialized equipment. The case study evidences that the use of mesopic photometry in con-junction with more appropriate technologies, such as LED luminaires, lead to a higher energy efficiency of the system.

- *Adjustment of Lighting Parameters from Photopic to Mesopic Values in Outdoor Lighting Installations Strategy and Associated Evaluation of Variation in Energy Needs* Enrique Navarrete-de Galvez 1*: Enrique Navarrete-de Galvez 1 , Alfonso Gago-Calderon 1,* , Luz Garcia-Ceballos 2 , Miguel Angel Contreras-Lopez 2 and Jose Ramon Andres-Diaz*

The sensitivity of the human eye varies with the different lighting conditions to which it is exposed. The cone photoreceptors perceive the color and work for illuminance conditions greater than 3.00 cd/m^2 (photopic vision). Below 0.01 cd/m^2 , the rods are the cells that assume this function (scotopic vision). Both types of photoreceptors work coordinately in the interval between these values (mesopic vision). Each mechanism generates a different spectral sensibility. In this work, the emission spectra of common sources in present public lighting installations are analyzed and their normative photopic values translated to the corresponding mesopic condition, which more faithfully represents the vision mechanism of our eyes in these conditions. Based on a common street urban configuration (ME6), a large set of simulations can be generated to determine the ideal light point setup configuration (luminance and light point height vs. poles distance ratio) for each case of spectrum source. Finally, the derived energy variation is analyzed from each design possibility. The results obtained may contribute to improving the criterion of light source selection and adapting the required regulatory values to the human eye vision process under normalized artificial street lighting condition, reaching an average energy saving of 15% and a reduction of 8% in terms of points of light required. They also offer a statistical range of energy requirements for lighting installation that can be used to generate accurate electrical designs or estimations without the necessity of defining the exact lighting configuration, which is 77.5% lower than conventional design criteria.

1.2 Problem Definition

Outdoor lighting installations incorporate different types of lamps such as High Pressure Sodium Vapour (HPSV or SON), Metal halide(MH) and LEDs. The luminance level generally lies in Mesopic zone for outdoor lighting. Adaptation luminance is also a factor for outdoor lighting. The performance for different lamps in outdoor lighting scenario under Mesopic luminance range and adaptation luminance of each lamp are studied and computed using a formulated mathematical modelling using the MATLAB and the IES files of different luminaires.

1.3 Objective

The objectives of the thesis are :

- To study the behaviour of different lamps under mesopic conditions.
- Simulation of Adaptation Luminance.

1.4 Methodology

- Measurement of photopic luminance and vertical illuminance under different lamp and adaptation conditions.
- Determination of S/P ratios, CCT & SPD of the lamps.
- Calculation of Mesopic Luminance
- Simulation of adaptation luminance using MATLAB software.
- Comparison of the obtained results by graphical and analytical comparative studies.

1.5 Outline of the Dissertation

Chapter 1 gives the introduction to the project. It also states the objective and methodology of the project.

Chapter 2 discusses the concepts of mesopic photometry.

Chapter 3 discusses the relation between mesopic photometry and outdoor lighting and gives idea about adaptation luminance.

Chapter 4 gives brief idea about the computational setup.

Chapter 5 deals with computation of values of Photopic Luminance and Mesopic Luminance and Adaptation Luminance.

Chapter 6 deals with Results and Analysis.

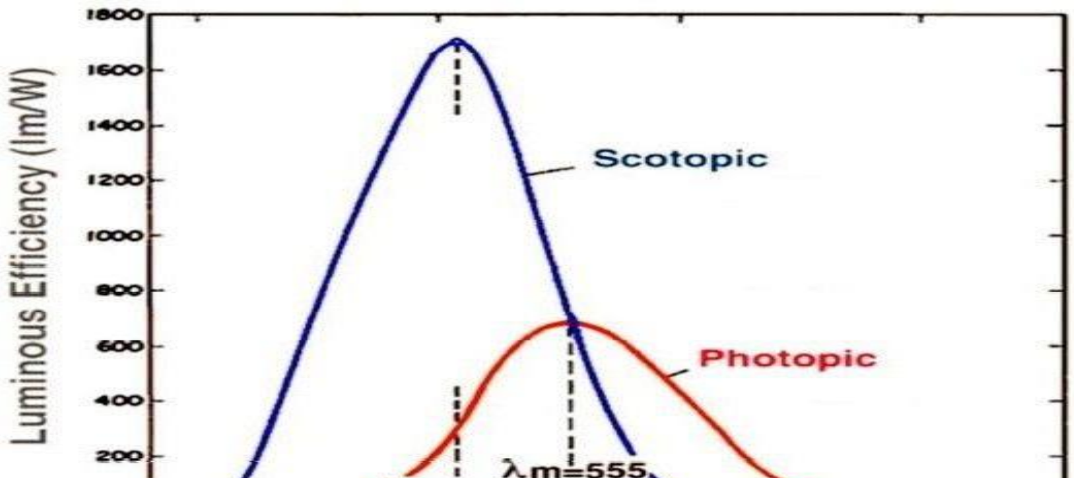
Chapter 7 draws the conclusion to the experiment and discusses the future scopes of the field of study.

CHAPTER 2:
MESOPIC PHOTOMETRY

2.1 Photometry CIE 191:2010

The aim of photometry is to measure light in such a way that the results correlate with human vision. Traffic signals and computer displays, for example, are meant for human eyes, and therefore, must be evaluated based on the spectral responsivity of the average human eyes. While radiometry covers all spectral regions from ultraviolet to infrared, photometry deals with only the spectral region from 380 to 780 nm (the visible region) where human eyes are sensitive. Photometry is essential for evaluation of light sources and objects used for lighting, signaling, displays, and other applications where light is seen by the human eye.

In order to achieve the aim of photometry, one must take into the characteristics of human vision. The relative spectral responsivity of the human eye was first defined by the Commission Internationale de l'E´clairage (CIE), (the International Commission on Illumination), in 1924. It is called the spectral luminous efficiency for photopic vision, with a symbol V(λ), defined in the domain from 380 to 780 nm, and is normalized to unity at its peak, 555 nm as shown in Fig.2.1. The luminance level is very high (luminance levels more than 5 cd/m^2) in the photopic vision and in the eyes cones are the dominant receptors. The spectral responsivity of human eyes deviates significantly at very low levels of luminance (luminance levels less than 0.005 cd/m^2) when the rods in the eyes are the dominant receptors. This type of vision is called scotopic vision. It's spectral responsivity, peaking at 507 nm, as shown in Fig 2.2, is designated as V'(λ) , and was defined by CIE in 1951[CIE 1951]. The human vision in the region between photopic vision and scotopic vision is called mesopic vision. At adaptation luminance levels between approximately 5 and 0.005 cd/m^2 both the cones and the rods are active. In the mesopic vision range, the activity of the rods becomes more important from high to low adaptation levels. As a result, the spectral sensitivity gradually shifts into the direction of small wavelength. In the mesopic vision range, light sources containing more cool white light than warm white light are more efficient for vision [Van Bommel 2015]. Claims are sometimes exaggerated and sometimes made when they are not valid at all. Such claims are valid for peripheral vision but not for on-line vision.



2

Fig 2.1 The Photopic and Scotopic Luminous Efficiency Functions

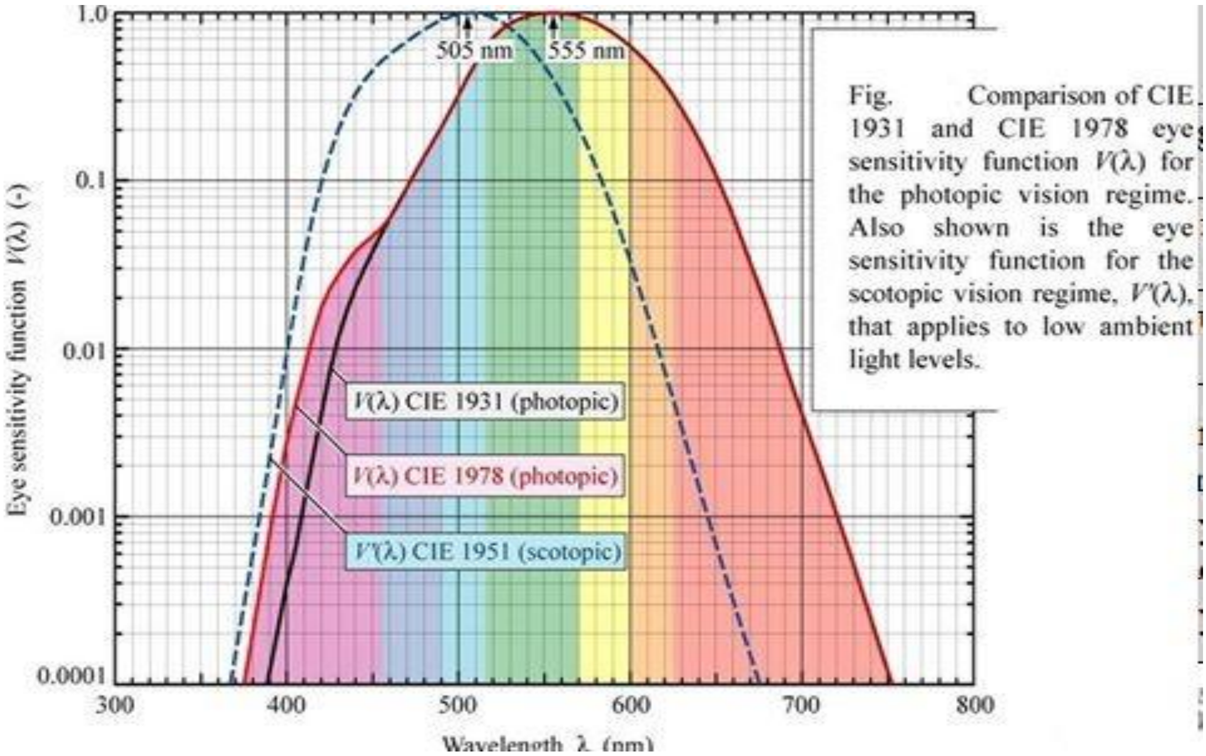


Fig 2.2 Photopic, Scotopic, and Mesopic Vision

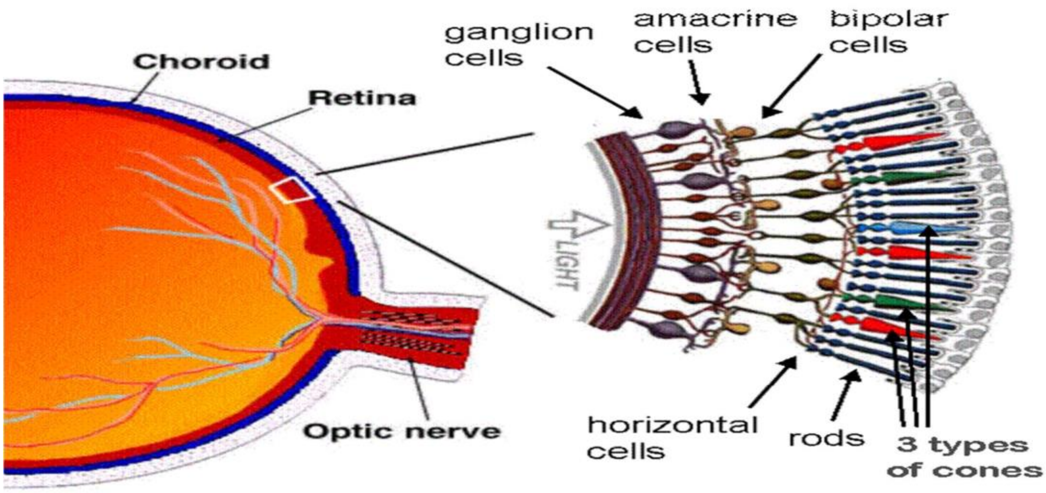


Fig 2.3 The Human Retina

Table2.0: Comparative study between Photopic,Scotopic ,Mesopic photometry

	Cones	**Rods**	**Cones and Rods**
Type of Vision	Photopic or “Day” vision	Scotopic or “night” vision	Mesopic or “dim light” vision
Colour Sensitivity	Full colour vision	Black and White vision	Some colour vision
Visual Acuity	Excellent visual acuity	Very poor visual acuity	Diminished visual acuity
Operating Range (Luminance and Illuminance)	3.4 cd/m^2 to 100,000+cd/m^2 (above approx. 1 to 2 lx such as under nearly all interior lighting conditions)	3.4 $x10^{-6}cd/m^2$ to 0.034 cd/m^2(approximately 0.21 lx, such as under a dark night sky)	0.034cd/m^2 to 3.4 cd/m^2(approximately 0.2to 1 or 2 lx, such as under bright moonlight)

2.2 S/P RATIO

The ratio of the luminous flux output of a light source evaluated according to the CIE scotopic spectral luminous efficiency function V’(λ), to the luminous flux output evaluated according to the CIE photopic spectral luminous efficiency function V(λ) is termed as the scotopic to photopic ratio, denoted as S/P ratio

$$\frac{S}{P} ratio = \frac{K'_m \int S_\lambda(\lambda)V'(\lambda)d\lambda}{K_m \int S_\lambda(\lambda)V(\lambda)d\lambda} \qquad (2.1)$$

Where ,
K'_m = 1700 lm/W is the maximum value of the spectral luminous efficacy for scotopic vision ,V’(λ) .

K_m= 683 lm/W is the maximum value of the spectral luminous efficacy for photopic vision, V(λ) .

$S_\lambda(\lambda)$ is the spectral power distribution of the light source. ‘λ’ is the wavelength.

2.3 MESOPIC VISION :HISTORY

Firstly, spectral luminous efficiency function for photopic vision V(λ) was introduced, then came the spectral luminous efficiency function for scotopic vision V'(λ), but there still existed a condition which is neither photopic nor scotopic. So, to fulfil the visual requirements and visual satisfaction under this condition, mesopic photometry was introduced.

Till the mid-1990s most of the research in this segment was based on brightness matching criterion between the target object and the surface adjacent to it. Seven of the nine initial models of mesopic photometry are based on this criterion. Later with the realization that, detection and recognition of the object is much more relevant than brightness matching, came the criterions based on visual task performance experiments. The first two mesopic models based on task performance show that under off-axis reaction time is dependent on the light spectrum whereas for on-axis the reaction time is independent of the spectrum of light. After that from a few more experiments it was clearly revealed that there exists a strong spectral effect in detection of off-axis target. The most remarkable finding of CIE mesopic system is the formation of a table where values of mesopic luminance corresponding to particular photopic luminance for all relevant S/P ratios are present. Though this table has an enormous importance, there is no clear instructions present to use it for practical application. Research is still going on in this domain to determine the most appropriate criterion of defining mesopic photometry.

The International Commission on Illumination (CIE) has published a recommendation for a performance based mesopic photometry system CIE 191:2010[CIE 2010]. The system provides a bridge between scotopic and photopic photometry. It has been developed with an emphasis on the visual performance in road and street lighting applications. According to the CIE 191 system, mesopic luminous efficiency $V_{mes}(\lambda)$ is a linear combination of the photopic $V(\lambda)$ and scotopic $V(\lambda)$ luminous efficiency functions.

2.3.1 Brief Description of Mesopic Models

In the past many attempts were made to develop a model for mesopic vision. Several authors have measured the spectral sensitivity functions in the mesopic domain (Walters and Wright, 1943; Kinney, 1958; Palmer, 1968; Kokoschka and Bodmann, 1975; Ikeda and Shimozono, 1981; Yaguchi and Ikeda, 1984; Sagawa and Takeichi, 1986; Sagawa and Takeichi, 1987; He et al., 1998)[CIE 2001]. All these studies proposed a specific spectral sensitivity as a function of the adaptation light level in the mesopic range. However, it appeared to be difficult to establish a consistent mesopic model. In 1989 the CIE published are port on the status of mesopic photometry, without actually establishing a standard model for mesopic vision (CIE, 1989). After that publication new methods and refinements of the existing models were proposed. In 2001 a new CIE report was published (CIE, 2001), updating the CIE publication of 1989. Seven mesopic models were addressed in this publication, which are based on 100 visual field and heterochromatic brightness matching (HCBM). Table 2.1 lists these mesopic models and their most important parameters, together with four mesopic models based on reaction time (RT) which were published elsewhere. With these models it is possible to calculate the so-called equivalent luminance, using various types of input variables. The equivalent luminance is defined as the luminance of the reference stimulus (formally with wavelength of nearly 555 nm, but also often a broadband white light) that appears equal to the test stimulus in brightness (CIE, 2001). The equivalent luminance has a better correlation to the visual impression or task performance than the common photopic luminance based on the $V(\lambda)$ function. Instead of the more formal term equivalent luminance, the term mesopic luminance will be used in this study to designate the output of mesopic models. The seven models are based on HCBM experiments in which the task of the subjects was to match the brightness of two parts of a static stimulus with a diameter of 10 degrees. The currently widely-used luminous efficiency function for photopic vision, $V(\lambda)$, is mainly based on flicker photometry using a 2-degreefield in which the two parts of the stimulus are compared by presenting them in an alternating mode. These differences in the tasks and conditions result in different shapes of the spectral sensitivity function in photopic conditions. A stimulus with a saturated colour (e.g. monochromatic blue or red) that has the same luminance as a white stimulus is perceived as brighter than the white stimulus. This effect is known as the Helmholtz–Kohlrausch effect (Wyszecki and Stiles, 1982). Therefore the spectral sensitivity functions based on photopic brightness matching are wider than the luminous efficiency function V(λ) which is incorporated in the vast majority of all luminance meters and illuminance meters. The spectral luminous efficiency function for scotopic vision, V'(λ), is determined by HCBM using a 20-degree field (CIE, 1983). Thus, because of differences in task and stimulus diameter, it is difficult to merge the sensitivity functions to a single model. There is no smooth connection between the existing spectral sensitivity data in the mesopic domain and the current spectral sensitivity standards for scotopic, V'(λ), at the lower end of the mesopic range, and for photopic vision, V(λ), at the higher end of the mesopic range. The problem of the difference in the field size can be solved by applying the spectral luminous efficiency function for the 10 degree CIE-observer,V10(λ),for the photopic domain, instead of the more generally used spectral luminous efficiency function for the 2- degree CIE-observer, V(λ).Another problem is that the spectral sensitivity functions based on brightness matching suffer from a failure of additive feature. Additive feature is essential for photometry (Abney's law). The additive problem can be tackled by using flicker photometry or a similar method. The V(λ) and V10(λ)functions are based on flicker photometry and have been shown to obey Abney's law (Wyszecki and Stiles, 1982). The models 8 and 9 are based on RT. The authors claim that these models do not suffer from the problems of models which are based on brightness matching (He et al., 1997, 1998).They state that in a reaction time task, just as in flicker photometry, the fast magnocellular channel, rather than the slow parvocellular channel, is being used. It is thought that the magnocellular channel is used for the fast transportation of the brightness signal; the parvocellular channel is slower and transports both the brightness and colour signals. Only the magnocellular channel appears to obey Abney's law of additivity. Therefore, the results of the reaction time experiments can be directly compared with luminance data obtained with the spectral luminous efficiency functions for photopic vision, V(λ) and V10(λ). As both He models include peripheral measurements these models make use of the wide field V10(λ) rather than the V(λ) for describing the luminance at photopic light levels. Foveal vision measured by reaction times might be modelled by V(λ) for any light level (He et al., 1997).

The reaction time task is directly linked to the performance task of driving a vehicle. One of the tasks of driving a vehicle is avoiding a potential hazard on the road and therefore a fast reaction is essential. Potential hazards, such as cars, pedestrians, and animals, do not always appear in front of the car, often they can come into view from the side. For that reason, off- axis detection is also important. The rods play an important role for off-axis detection, so the photopic luminance based on the V(λ) function is inadequate. It should be noted that the first seven models in Table 3.a. do not account for the eccentricity of the stimulus, i.e. eccentricity is not a parameter in the model. Models 8, 9, 10, and 11 are all based on reaction time measurements of two studies (He et al., 1997, 1998) .

$$V_{mes}(\lambda, L_{mes}) = k\{x(L_{mes})V_{10}(\lambda) + [1 - x(L_{mes})]V'(\lambda)\} \quad (2.2)$$

Which ensures that the maximum value of Vmes(λ) is unity. The mesopic luminance, Lmes, is calculated by applying the calculated spectral luminous efficiency function for mesopic vision in the integration over the visual part of the spectrum

$$L_{mes} = K_{mes} \int V_{mes}(\lambda, L_{mes} L_e(\lambda) d\lambda \quad (2.3)$$

The factor Kmes is equal to 683 lm/W divided by the value of Vmes(λ) for a wavelength of λ= 555 nm and Le(λ) is the spectral radiance in W m-2 s-1. Note that the light level used to calculate the weighting factor x in turn is used as mesopic luminance. Hence, the calculation of the mesopic luminance is a complicated iterative algorithm that must be repeated until a sufficiently accurate value of Lmes is obtained.

Model 9 differs from model 8 because of a slightly different function for the weighting factor. The algorithm is also iterative and more complicated because the light level is expressed as mesopic retinal illuminance rather than as mesopic luminance. Model 9 also determines the spectral luminous efficiency function for mesopic vision, Vmes(λ), by weighting the spectral luminous efficiency functions V'(λ) and V10(λ).Model 10 is designed according to the same weighting principle as applied in models 8 and 9. The difference is that now the more common efficiency function for photopic vision for a 2-degree field size, V(λ), is used instead of V10(λ). The second simplification is that the weighting factor is a function of the photopic luminance L and the ratio of scotopic and photopic luminance, S/P(2-degree observer). Therefore, the calculation procedure is not iterative. Model 11, the unified luminance model, is the simplest model (Rea et al., 2004), which only needs the photopic luminance and scotopic luminance as input, rather than the spectral radiance data as in previous models. The model consists of a closed form equation and the calculation is not iterative. As the reaction time task is highly relevant for traffic, and additivity is preserved, it can be concluded that spectral Model 8 is based on the calculation of the spectral luminous efficiency function for mesopic vision, Vmes(λ),by weighting the spectral luminous efficiency function for scotopic vision, V'(λ), and the spectral luminous efficiency function for photopic vision with 10 degrees' field size, V10(λ) according to equation:

The weighting factor, x, depends on the light level. The factor k is a normalization constant sensitivity determined with a reaction time task would seem to be a promising candidate for a mesopic model.

Table 2.1 A list of Mesopic models in the 2001 CIE report (No. 1–7) and the models of He and Rea (No. 8–11) [Eloholma 2005]

No.	Model	Field diameter (degrees)	Task	Eccentricity (degrees)	Input variables	References
1.	Palmer 1	10	HCBM	0	L_{10} ,L'	Palmer,1968
2.	Palmer 2	10	HCBM	0	L_{10} ,L'	CIE,1989,2001
3.	Sagawa-Takeichi	10	HCBM	0	L_{10} ,L', X,Y,Z	Ikeda and Shimozono,1981; CIE 1989
4.	Nakano-Ikeda	10	HCBM	0	L', X10,Y10,Z 10	Sagawa and Takeichi,1987,1992
5.	Kokoschka-Bodmann	10	HCBM	0	L', X10,Y10,Z 10	Kokoschka and Bodmann,1975; Kokoschka 1980
6.	Trezona	10	HCBM	0	L', X10,Y10,Z1 0	Trezona, 1987,1990
7.	Ashizawa	10	HCBM	0	V_{10}(λ),V'(λ)	Ashizawa et al,1985

8.	He 1	2	RT	15	$L_e(\lambda)$	He et al 1997
9.	He 2	2	RT	12	$L_e(\lambda)$	He et al 1998
10	Rea	2	RT	Non-foveal	$L_e(\lambda)$	Rea et al 2003
11	Unifl	2	RT	Non-foveal	L_e ,L	Rea et al 2004

2.4 RECOMMENDED SYSTEM FOR PERFORMANCE BASED MESOPIC PHOTOMETRY

The recommended system for visual performance based mesopic photometry describes spectral luminous efficiency, Vmes(λ), in the mesopic region as a linear combination of the photopic spectral luminous efficiency function, V(λ), and the scotopic spectral luminous efficiency function, V'(λ), and establishes a gradual transition between these two functions throughout the mesopic region. The system is of the form:

$$V_{mes,L(\lambda)} = \frac{mV(\lambda) + (1-m)V'(\lambda)}{M(m)} \qquad \text{for } 0 \leq m \leq 1 \qquad (2.4)$$

$$L_{mes} = \frac{683}{V_{mes}(\lambda_0)} V_{mes} L(\lambda) L_e(\lambda) d\lambda \qquad (2.5)$$

M(x) is a normalizing function such that Vmes(λ) attains a maximum value of 1 Vmes(λ_0) is the value of Vmes(λ) at 555 nm

Lmes is the mesopic luminance

Le(λ) is the spectral radiance in W•m-2•sr-1•nm-1 ifLmes ≥ 5.0 cd·m-2, then m = 1

ifLmes ≤ 0.005 cd·m-2, then m = 0

The coefficient m and the mesopic luminance, Lmes, can be calculated using an iterative approach as follows:

$m_0 = 0.5$

$$L_{mes,n} = \frac{m_{(n-1)} L_p + (1 - m_{(n-1)}) L_s V'(\lambda_0)}{m_{(n-1)} + (1 - m_{(n-1)}) V'(\lambda_0)} \qquad (2.6)$$

$$m_n = a + b\log_{10}(L_{mes,n}) \qquad \text{for } 0 \leq m \leq 1$$

Where Lp is the photopic luminance, Ls is the scotopic luminance, and V′(λ0) = 683/1699 is the value of scotopic spectral luminous efficiency function at λ0=555 nm, a and b are parameters which have the values a = 0.7670 and b = 0.3334, and n is the iteration step.

The values of m and Lmes for this system as a function of photopic luminance and light source S/P-ratio (ratio of scotopic-to-photopic luminous output) are given in Table 2.2.

The system is proposed for evaluation of lighting for visual tasks in the peripheral region of the visual field in the mesopic region; it is recommended that on-axis tasks, where foveal vision is dominant, should be evaluated using the photopic spectral luminous efficiency function, V(λ).

The requirement of the recommended system is that it should (within limits) provide a result that is meaningful in relation to human visual psychophysics and provide a correlation with visual performance under a range of different conditions. The degree of correlation with task performance was used as one criterion in determining the recommended system. The other criteria were the practical utility of the system and the requirement that it should maintain additivity, which is an underlying requirement of CIE photometry. The recommended system is an intermediate between the USP- (Rea et al 2004) and MOVE-systems (Goodman et al 2007) and (similarly to them) describes mesopic spectral luminous efficiency in terms of a linear combination of the photopic and scotopic spectral luminous efficiency functions that provides a gradual transition between these functions through the mesopic region. The mesopic spectral luminous efficiency functions derived using this system are additive in nature and provide a bridge between the current photopic and scotopic functions, with the further advantage of being relatively easy to implement in a practical measurement system, as well as providing a meaningful correlation with actual task performance. Thus this recommended system represents an effective and practical solution to mesopic photometry, based upon more than a decade of visual psychophysical studies and nearly a century of photometric metrology principles.

Table 2.2 a) Adaptation Coefficient m and b) Lmes of the recommended mesopic system as a function of photopic luminance and S/P-ratio of light source

a

	m	Photopic luminance cd·m^{-2}						
	S/P	0,01	0,03	0,1	0,3	1	3	4,5
LPS –	0,25		0,1542	0,3830	0,5644	0,7538	0,9225	0,9841
	0,35		0,1804	0,3920	0,5688	0,7558	0,9230	0,9842
	0,45	0,0000	0,1992	0,4000	0,5730	0,7576	0,9235	0,9843
HPS –	0,55	0,0190	0,2140	0,4073	0,5770	0,7594	0,9240	0,9844
	0,65	0,0459	0,2265	0,4139	0,5808	0,7612	0,9245	0,9845
	0,75	0,0655	0,2373	0,4201	0,5844	0,7629	0,9249	0,9846
	0,85	0,0812	0,2468	0,4258	0,5878	0,7646	0,9254	0,9846
	0,95	0,0943	0,2553	0,4311	0,5911	0,7662	0,9258	0,9847
	1,05	0,1057	0,2631	0,4361	0,5942	0,7678	0,9263	0,9848
MH warm	1,15	0,1157	0,2702	0,4408	0,5972	0,7693	0,9267	0,9849
white ~	1,25	0,1247	0,2767	0,4452	0,6001	0,7708	0,9272	0,9850
	1,35	0,1329	0,2828	0,4494	0,6029	0,7723	0,9276	0,9851
	1,45	0,1404	0,2885	0,4534	0,6056	0,7737	0,9280	0,9852
	1,55	0,1473	0,2939	0,4573	0,6082	0,7751	0,9284	0,9853
	1,65	0,1538	0,2990	0,4609	0,6107	0,7764	0,9289	0,9853
	1,75	0,1598	0,3038	0,4645	0,6131	0,7778	0,9293	0,9854
	1,85	0,1654	0,3083	0,4678	0,6155	0,7791	0,9297	0,9855
	1,95	0,1708	0,3126	0,4711	0,6178	0,7803	0,9301	0,9856
	2,05	0,1758	0,3168	0,4742	0,6200	0,7816	0,9304	0,9857
	2,15	0,1806	0,3207	0,4772	0,6221	0,7828	0,9308	0,9857
	2,25	0,1852	0,3245	0,4801	0,6242	0,7840	0,9312	0,9858
MH day-	2,35	0,1895	0,3282	0,4830	0,6263	0,7852	0,9316	0,9859
light –	2,45	0,1937	0,3317	0,4857	0,6283	0,7863	0,9319	0,9860
	2,55	0,1977	0,3351	0,4883	0,6302	0,7875	0,9323	0,9860
	2,65	0,2015	0,3383	0,4909	0,6321	0,7886	0,9327	0,9861
	2,75	0,2052	0,3415	0,4934	0,6339	0,7896	0,9330	0,9862

b

	L_{mes} S/P	Photopic luminance cd·m^{-2} 0,01	0,03	0,1	0,3	1	3	4,5
LPS ~	0,25	0,0025	0,0145	0,0705	0,2467	0,9130	2,9265	4,4782
	0,35	0,0035	0,0174	0,0750	0,2545	0,9253	2,9367	4,4812
	0,45	0,0045	0,0198	0,0793	0,2620	0,9373	2,9468	4,4842
HPS ~	0,55	0,0057	0,0220	0,0834	0,2693	0,9492	2,9568	4,4872
	0,65	0,0069	0,0239	0,0873	0,2764	0,9608	2,9666	4,4901
	0,75	0,0079	0,0258	0,0911	0,2833	0,9722	2,9763	4,4929
	0,85	0,0088	0,0275	0,0947	0,2901	0,9835	2,9859	4,4958
	0,95	0,0096	0,0292	0,0983	0,2967	0,9945	2,9953	4,4986
	1,05	0,0104	0,0308	0,1017	0,3032	1,0054	3,0046	4,5014
MH warm white ~	1,15	0,0111	0,0323	0,1051	0,3096	1,0161	3,0139	4,5041
	1,25	0,0118	0,0338	0,1083	0,3158	1,0267	3,0230	4,5068
	1,35	0,0125	0,0353	0,1115	0,3220	1,0371	3,0319	4,5095
	1,45	0,0132	0,0367	0,1147	0,3280	1,0473	3,0408	4,5122
	1,55	0,0138	0,0381	0,1178	0,3339	1,0575	3,0496	4,5148
	1,65	0,0145	0,0395	0,1208	0,3398	1,0674	3,0582	4,5174
	1,75	0,0151	0,0408	0,1238	0,3455	1,0773	3,0668	4,5200
	1,85	0,0157	0,0421	0,1267	0,3512	1,0870	3,0753	4,5225
	1,95	0,0163	0,0434	0,1295	0,3568	1,0966	3,0836	4,5250
	2,05	0,0169	0,0446	0,1324	0,3623	1,1060	3,0919	4,5275
	2,15	0,0174	0,0459	0,1352	0,3677	1,1154	3,1001	4,5299
	2,25	0,0180	0,0471	0,1379	0,3731	1,1246	3,1082	4,5323
MH day-light ~	2,35	0,0185	0,0483	0,1406	0,3784	1,1338	3,1162	4,5347
	2,45	0,0191	0,0495	0,1433	0,3836	1,1428	3,1241	4,5371
	2,55	0,0196	0,0506	0,1459	0,3888	1,1517	3,1319	4,5395
	2,65	0,0201	0,0518	0,1485	0,3939	1,1605	3,1396	4,5418
	2,75	0,0207	0,0529	0,1511	0,3989	1,1693	3,1473	4,5441

2.5 RECOMMENDED SYSTEM FOR PERFORMANCE BASED MESOPIC PHOTOMETRY

The foundations for any system of photometry must lie in empirical visual performance data using human subjects. Photometry has always had its roots in human visual psychophysics. Significantly, however, the current system of photometry is truly representative of the spectral sensitivity of human vision for only a very limited number of visual tasks. The spectral sensitivity of the visual system for mesopic vision is not well represented by either of the spectral luminous efficiency functions, V(λ) and V´(λ), that currently underlie photometry.

It is worth noting that no single system can ever hope to provide a complete prediction of visual performance for all tasks and lighting conditions. Vision is a hugely complicated process and the spectral luminous efficiency of the eye is influenced by a large number of factors. These factors include size and location of the stimulus in the visual field, ambient light level and spectrum, stimulus contrast and spectrum, and speed of response required by the task being conducted. Changing any of these parameters will change the efficiency of the visual system and the ability to perform the requisite task (Rea and Bullough 2007, Eloholma 2005).

Instead of trying to describe the detailed performance of the eye under a given set of conditions, the emphasis in this Technical Committee has been on developing a system of photometry for the mesopic region which can be readily implemented in practice, but which may not provide a precise description of visual performance. This places two important constraints on the system:

- It must be additive

- It must tend to V(λ) at the upper end of the mesopic region and to V′(λ) a the lower end

The simplest form of a system for mesopic photometry that satisfies these constraints is a linear combination of the photopic and scotopic spectral luminous efficiency functions, of the form:

$$V_{mes} = yV(\lambda) + (1-y)V'(\lambda) \qquad (2.7)$$

y being a function of luminance.

The mesopic spectral sensitivity functions, Vmes(λ), defined by such a system are, by definition, additive in nature (since both V(λ) and V′(λ) are additive), but it must be remembered that due to the dependence of mesopic spectral sensitivity on the state of adaptation of the eye, additivity applies only within a given adaptation level.

The two recently proposed visual performance based systems for mesopic photometry, namely the USP-system (Rea et al. 2004) and the MOVE-system (Goodman et al., 2007), both take the form presented above, thus bridging the photopic and scotopic domains and preserving the fundamental requirement of additivity. The different experimental conditions underlying these two systems result in differences between the systems, a major difference being the transition point between the mesopic and photopic regions. Also, the different characteristics of the adaptation coefficient (designated X in the USP-system, and x in the MOVE-system), result in different predictions of mesopic values calculated with the two systems. In addition to the USP- and MOVE-systems, an Intermediate system is also considered in this report. The Intermediate system has the form presentedabove, and like the MOVE-system has a log- linear relationship between 'y' and mesopic luminance,but has adjusted upper and lower luminance limits for the mesopic region .

2.5.1. USP System

Two investigations by He et al. (1997, 1998) form the experimental basis of the USP-system. In the first work of He et al. (1997) reaction times were measured monocularly under two light sources (HPS and MH) at eight luminance levels between 0.003 cd/m2 and 10 cd/m2. A target contrast of C = 2.3, was used in the experiments. The spectral power distributions of the test target and the adaptation backgrounds were the same i.e. the only information available to the visual system was the achromatic content of the stimulus. (More specifically, the tasks involved luminance contrast with no colour contrast.) The resultant system was a linear combination of the scotopic V′(λ) and the 100photopic V10(λ) functions. The system is based on reaction time data for two subjects. According to He et al. (1997) visual inspection of the two subjects' off-axis reaction time data showed a separation between the two light

sources below 0.3 cd/m2, but no clear separation was observed above 1 cd/m2. As the midpoint between these luminancesluminance in log units is 0.6 cd/m2, and the paper described that the rod-cone discontinuity at about this luminance, the 0.6 cd/m2 luminance value was chosen by

He et al. as a convenient point of bifurcation on fitting the data curves. Based on the reaction time data, He et al. concluded that there is no rod contribution above 0.6 cd•m-2 to the reaction time task investigated. An independent study of Bierman et al. (1998) confirmed the reaction time data of He et al. (1997) by using reaction time differences of the two eyes as the criterion.

In the second work by He et al. (1998) mesopic spectral luminous efficiency functions of one subject were measured using a method of reaction time differences between the two eyes. In this binocular simultaneity method, luminous efficiencies for five quasi-monochromatic stimuli (half bandwidth of 10 nm, peaks at 436 nm, 470 nm, 510 nm, and 630 nm) were measured against a yellow reference field (monochromatic 589 nm) at three light levels (0.3 Td, 3 Td, 10 Td). Thus in this experimental study the spectral power distribution of the reference field was different from that of the test field and each eye was adapted to a different condition (i.e. light level and wavelength).The derived mesopic spectral luminous efficiency functions were fitted with the linear model developed in the earlier work of He et al. (1997). The transition point between mesopic and photopic regions was not reached within the retinal illuminance range studied (0.3 Td, 3 Td, 10 Td). Using a relationship between adaptation coefficient and retinal illuminance, the transition point for the data of the one subject in

question was estimated to occur at 21 Td, corresponding to a luminance level of 1.7 cd/m2.

The latter study of He et al. (1998) resulted in an iterative computational procedure for

calculating mesopic light levels. In this procedure, the transition point between mesopic and photopic regions occurs at 21 Td. When the monocular viewing used in the previous study by He et al. (1997) is transferred to correspond to binocular viewing conditions, the transition

point of 0.6 cd/m2 corresponds to a retinal illuminance value of 25 Td as remarked by He et

al. (1998).

Table 2.3 The experimental conditions underlying the USP-system (He et al. 1997, He et al. 1998)

Method	Stimuli	Contrast	Luminance	Subject	
RT	MH and HPS	2.3	0.003-10 cd/m^2	2	3
RT	470,510,546,630 nm	2.3	0.3,3,10 Td	1	

Half bandwidth = 10 nm C = $(L_t - L_b)/L_b$

The USP formulation is proposed by Rea et al. (2004) as a unified system of photometry. In the mesopic region the parameter X is used to calculate mesopic luminous efficiency $V_{mes}(\lambda)$ as a linear transition between the scotopic V’(λ) and the photopic V(λ) functions and is of the form

$$V_{mes}(\lambda) = XV(\lambda) + (1-X)V'(\lambda) \qquad \text{for } 0 \le X \le 1 \;) \qquad (2.8)$$

where Vmes(λ) is the mesopic spectral luminous efficiency function under the given conditions, V(λ) is the photopic spectral luminous efficiency function, V’(λ) is the scotopic spectral luminous efficiency function, and X is a parameter characterizing the relative proportions of the photopic and scotopic luminous efficiency at any luminance level. In the scotopic region the USP-system is equivalent to current scotopic photometry and in the photopic region it is equivalent to current photopic photometry, as also are the other systems described in this report.

In proposing the USP-system Rea et al. (2004) made several simplifications to the approaches of the works of He et al. Firstly, since the pupil size is large and essentially constant below 1

cd/m2, it was assumed that a constant pupil diameter of 7 mm could be taken to apply, so that

the transition point between the mesopic and photopic regions determined from each of the

two studies (He et al. 1997, He et al. 1998) are in substantial agreement. This led to the choice of 0.6 cd/m2 as the transition point between the mesopic and photopic regions. Secondly, the relationship between the coefficient X and mesopic luminance was assumed to be linear between 0.001 cd/m2 and 0.6 cd/m2 in order to develop a closed-form solution for

X. And thirdly, in the final form of the USP-system, V10(λ) was substituted by V(λ), based on

the observation that for most practical conditions photometric quantities based on V(λ) and V10(λ) do not differ substantially.

Below equations give the closed-form expression for calculating the mesopic luminance Lmes

and the corresponding coefficient X.

$$L_{mes} = 0.834L_p - 0.335L_s - 0.2 + \sqrt{0.696L_p^2 - 0.333L_p - 0.56L_pL_s + 0.113L_s^2 + 0.537L_s + 0.04} \quad (2.9)$$

For $0.001 < L_{mes} < 0.6$

$$X = mL_{mes} + \beta \qquad \text{for } 0 \le X \le 1 \quad (3.0)$$

Where Lp is the photopic luminance, Ls is the scotopic luminance, and m and β are coefficients given by m = 1/0.599 and β = -0.001/0.599 (Rea et al 2004).

The values of X and Lmes given by the USP-system as a function of photopic luminance and light source S/P-ratio are presented in Table 2.3. The lamp notations LPS (low pressure sodium), HPS (high pressure sodium) and MH (metal halide) on the left side of the table refer to the typical regions of S/P-ratios of these lamp types.

Table 2.4 a) The values of X given by the USP-system as a function of photopic luminance and S/P-ratio, b)values of Lmes given by the USP-system as a function of photopic luminance and S/P-ratio (Rea et al. 2004)

a

	x	Photopic luminance cd·m^{-2}						
	S/P	0,001	0,003	0,01	0,03	0,1	0,3	0,55
LPS ~	0,25		0,0000	0,0026	0,0119	0,0562	0,3306	0,8811
	0,35		0,0001	0,0043	0,0172	0,0749	0,3652	0,8876
	0,45		0,0006	0,0060	0,0223	0,0919	0,3938	0,8934
HPS ~	0,55		0,0011	0,0076	0,0273	0,1074	0,4183	0,8986
	0,65		0,0016	0,0093	0,0322	0,1218	0,4397	0,9032
	0,75		0,0021	0,0110	0,0370	0,1352	0,4588	0,9075
	0,85		0,0026	0,0126	0,0416	0,1477	0,4761	0,9113
	0,95		0,0031	0,0142	0,0462	0,1595	0,4917	0,9149
	1,05	0,0001	0,0036	0,0158	0,0506	0,1707	0,5061	0,9181
MH warm	1,15	0,0002	0,0041	0,0174	0,0549	0,1814	0,5194	0,9211
white ~	1,25	0,0004	0,0046	0,0190	0,0592	0,1915	0,5318	0,9239
	1,35	0,0006	0,0051	0,0206	0,0634	0,2011	0,5433	0,9264
	1,45	0,0007	0,0056	0,0221	0,0675	0,2104	0,5541	0,9288
	1,55	0,0009	0,0060	0,0237	0,0715	0,2192	0,5643	0,9311
	1,65	0,0011	0,0065	0,0252	0,0754	0,2278	0,5739	0,9332
	1,75	0,0012	0,0070	0,0267	0,0793	0,2360	0,5830	0,9352
	1,85	0,0014	0,0075	0,0282	0,0831	0,2439	0,5915	0,9370
	1,95	0,0016	0,0080	0,0297	0,0868	0,2516	0,5997	0,9388
	2,05	0,0017	0,0085	0,0312	0,0905	0,2590	0,6075	0,9404
	2,15	0,0019	0,0090	0,0327	0,0941	0,2661	0,6149	0,9420
	2,25	0,0021	0,0094	0,0342	0,0977	0,2730	0,6220	0,9435
MH day-	2,35	0,0022	0,0099	0,0356	0,1012	0,2798	0,6287	0,9449
light ~	2,45	0,0024	0,1040	0,0371	0,1046	0,2863	0,6352	0,9462
	2,55	0,0026	0,0109	0,0385	0,1080	0,2929	0,6415	0,9475
	2,65	0,0027	0,0114	0,0400	0,1140	0,2989	0,6474	0,9487
	2,75	0,0029	0,0118	0,0414	0,1147	0,3049	0,6532	0,9499

b

	L_{mes}	Photopic luminance cd·m^{-2}						
	S/P	0,001	0,003	0,01	0,03	0,1	0,3	0,55
LPS ~	0,25	0,0002	0,0007	0,0025	0,0082	0,0347	0,1990	0,5288
	0,35	0,0003	0,0010	0,0036	0,0113	0,0459	0,2198	0,5327
	0,45	0,0004	0,0014	0,0046	0,0114	0,0560	0,2369	0,5362
HPS ~	0,55	0,0005	0,0017	0,0056	0,0174	0,0653	0,2516	0,5393
	0,65	0,0006	0,0020	0,0066	0,0203	0,0739	0,2644	0,5420
	0,75	0,0007	0,0023	0,0076	0,0231	0,0820	0,2758	0,5446
	0,85	0,0008	0,0026	0,0085	0,0259	0,0895	0,2862	0,5469
	0,95	0,0009	0,0028	0,0095	0,0286	0,0966	0,2956	0,5490
	1,05	0,0010	0,0031	0,0105	0,0313	0,1033	0,3042	0,5509
MH warm	1,15	0,0011	0,0034	0,0114	0,0339	0,1096	0,3121	0,5527
white ~	1,25	0,0012	0,0037	0,0124	0,0365	0,1157	0,3196	0,5544
	1,35	0,0013	0,0040	0,0133	0,0390	0,1215	0,3265	0,5559
	1,45	0,0014	0,0043	0,0143	0,0414	0,1270	0,3329	0,5574
	1,55	0,0015	0,0046	0,0152	0,0438	0,1323	0,3390	0,5587
	1,65	0,0016	0,0049	0,0161	0,0462	0,1374	0,3448	0,5600
	1,75	0,0017	0,0052	0,0170	0,0485	0,1424	0,3502	0,5612
	1,85	0,0018	0,0055	0,0179	0,0508	0,1471	0,3553	0,5623
	1,95	0,0019	0,0058	0,0188	0,0530	0,1517	0,3602	0,5633
	2,05	0,0020	0,0061	0,0197	0,0552	0,1561	0,3646	0,5643
	2,15	0,0021	0,0064	0,0206	0,0574	0,1604	0,3693	0,5653
	2,25	0,0022	0,0067	0,0215	0,0595	0,1646	0,3736	0,5662
MH day-	2,35	0,0023	0,0069	0,0224	0,0616	0,1686	0,3776	0,5670
light ~	2,45	0,0024	0,0072	0,0232	0,0637	0,1725	0,3815	0,5678
	2,55	0,0025	0,0075	0,0241	0,0657	0,1763	0,3852	0,5686
	2,65	0,0026	0,0078	0,0249	0,0667	0,1800	0,3888	0,5693
	2,75	0,0027	0,0081	0,0258	0,0697	0,1836	0,3923	0,5700

2.5.2. MOVE System

The MOVE-system proposed by the MOVE consortium (Eloholma et al. 2005, Goodman et al. 2007) is based on an empirical multi-technique approach, where the task of night-time driving was divided into three visual subtasks, which are related to the detection of a visual target, the speed of detection, and the identification of the details of the target. Both chromatic and achromatic targets were included. Thus, unlike the approach taken for the USP- system, the MOVE- system is based on data from tasks that do not inherently obey the laws of additivity. This approach was taken in an attempt to provide a reasonably accurate characterization of visual effectiveness for a wide range of 'realistic' visual tasks, i.e. tasks involving the chromatic as well as the achromatic channels of the human visual system. Like the USP- system, however, a major constraint on the system was that it should be able to be readily implemented in practice, and it was therefore recognized that it could not provide a precise description of visual response for any of the tasks considered.

The detection of a visual target is related to the achromatic threshold (Freiding et al. 2007),

i.e. to increments and/or decrements of the visual target's intensity around the threshold. Achromatic detection thresholds were measured using three experimental setups: modified Goldman perimeter (TKK Helsinki University of Technology, Finland), large homogenous screen (TUD Darmstadt University of Technology, Germany), and screen with computer controlled projector (UP University of Pannonia, Hungary).

The speed of detection is related to reaction times (Walkey et al. 2007). Reaction time data were measured using four different experimental setups: large uniform hemisphere (TKK, Finland), computer controlled CRT display (CU City University, UK), driving simulator (TNO Human Factors, The Netherlands), and large homogenous screen (TUD, Germany).

The identification of the targets is related to achromatic recognition threshold (Várady et al. 2007). These data were measured using a screen with computer-controlled projector (UP, Hungary).

A common set of parameter values were used as the basis of each particular data set generated at each of the different test locations. The joint parameters were: background

photopic luminances 0.01 cd/m2, 0.1 cd/m2, 1 cd/m2, and 10 cd/m2(some experiments also

used 0.3 cd/m2and 3 cd/m2), target eccentricities 0° and 10°, target size 2° (and 0.29°), and

nearly steady presentation $\Delta t \geq 3s$ (or $\Delta t \leq 500$ ms for some of the reaction time experiments).

The contrasts were at or near threshold and both quasi-monochromatic (half bandwidth = 10 nm) and broadband light sources were used. For some of the experiments the target and background had the same spectral characteristics (achromatic conditions) whereas the majority used different colours for the target and background (chromatic conditions). Altogether 109 subjects participated in the experiments. Table 2.4 summarises the parameters and experimental conditions underlying the MOVE-system.

Table 2.5 The experimental conditions underlying the contrast threshold (CT), reaction time (RT) and recognition threshold (RGT) experiments of the MOVE-system (Eloholma 2005, Goodman et al., 2007). The experiments were carried out in different laboratories

Method	Stimuli	Contrast	Luminance(cd/m^2)	Subject

CT	380-700 nm steps 450-700 nm steps blue,green,red(100 nm bands)	At threshold At threshold At threshold	0.01-10 0.01-1 0.01-10	6 10 19	
RT	466, 503, 522, 594, 638 nm various broadband broadb. white, yellow, red, blue 380-700 nm, 10 nm steps	0.05-3 Varied 0.14 Near threshold	0.01-10 0.01-10 0.01-10 0.3-1	23 11 23 7	109
RGT	450-700 nm ,10 nm steps	At threshold	0.01-1	10	

It was foreseen in the MOVE work that the spectral response for each visual sub-task might require a distinct description of mesopic spectral sensitivity. Results from each of the three visual sub-tasks were therefore initially modelled separately, with each background level taken in turn. It was subsequently found, however, that an acceptably good fit to all the data sets was obtained with a single model.

The data from the vision experiments of the MOVE project resulted in a linear system for mesopic photometry characterizing the mesopic spectral sensitivity of peripheral vision (Goodman et al. 2007):

$$M(X)V(\lambda) = xV(\lambda) + (1-x)V'(\lambda) \quad \text{for } 0 \leq x \leq 1 \qquad (3.1)$$

where M(x) is a normalizing function such that the Vmes(λ) function attains a maximum value of 1, Vmes(λ) is the mesopic spectral luminous efficiency function under the given conditions, V(λ) is the photopic spectral luminous efficiency function, V'(λ) is the scotopic spectral luminous efficiency function, and x is a coefficient dependent on the luminance level and spectrum.

The experimental data generated within the MOVE project indicated that mesopic vision extends to approximately 10cd/m2, although the differences between mesopic and photopic spectral sensitivity become smaller with increasing luminance. The MOVE-system places the transition between the mesopic and photopic regions at approximately 10 cd/m2, and the

transition between the mesopic and scotopic at approximately 0.01cd/m2, though both the upper- and lower limits are dependent on the S/P-ratio as well.

The coefficient x and mesopic luminance Lmes of the MOVE-system are determined iteratively as follows:

$$X_{n+1} = a + b\log_{10}[\frac{1}{M(x_n)}(x_n \frac{L_p}{K_p} + (1-x_n)\frac{L_s}{K_s}] \quad \text{for } 0 \le x \le 1 \qquad (3.2)$$

$$L_{mes} = \frac{xL_p + (1-x)L_s V'(\lambda_0)}{x + (1-x)V'(\lambda_0)} \qquad (3.3)$$

where a and b are parameters which have the values a = 1.49 and b = 0.282, Lp is the photopic luminance, Ls is the scotopic luminance, Kp is the photopic maximum luminous efficacy (Kp = 683 lm•W-1), Ks is the scotopic maximum luminous efficacy (Ks =1699lm/W), Lmes is the mesopic luminance, and V´(λ0) = 683/1699 is the value of scotopic spectral sensitivity function at λ0=555 nm, which is the wavelength where photopic spectral sensitivity function attains its maximum V(λ0) = 1. The normalizing function M(x) can be approximated as follows:

$$M(x) = \max[xV(\lambda) + (1-x)V'(\lambda)] \approx 1 - 0.65x + 0.65x^2$$

The values of x and Lmes given by the MOVE-system as a function of photopic luminance and light source S/P-ratio are presented in Table 2.6.

Table 2.6 a) The values of x given by the MOVE-system as a function of photopic luminance and S/P-ratio, b) values of Lmes given by the MOVE-system as a function of photopic luminance and S/P-ratio

a

	x	Photopic luminance cd·m^{-2}						
	S/P	0,01	0,03	0,1	0,3	1	3	10
LPS ~	0,25		0,0000	0,3080	0,4900	0,6660	0,8160	0,9720
	0,35		0,0700	0,3200	0,4950	0,6690	0,8170	0,9720
	0,45		0,1090	0,3300	0,5010	0,6710	0,8180	0,9720
HPS ~	0,55		0,1330	0,3400	0,5050	0,6740	0,8190	0,9720
	0,65		0,1510	0,3480	0,5100	0,6760	0,8200	0,9720
	0,75		0,1660	0,3550	0,5140	0,6780	0,8210	0,9720
	0,85	0,0000	0,1780	0,3620	0,5180	0,6800	0,8220	0,9730
	0,95	0,0120	0,1890	0,3680	0,5220	0,6830	0,8230	0,9730
	1,05	0,0280	0,1980	0,3740	0,5260	0,6850	0,8240	0,9730
MH warm white ~	1,15	0,0410	0,2070	0,3790	0,5290	0,6870	0,8250	0,9730
	1,25	0,0530	0,2150	0,3840	0,5320	0,6880	0,8260	0,9730
	1,35	0,0630	0,2220	0,3890	0,5360	0,6900	0,8270	0,9730
	1,45	0,0720	0,2290	0,3940	0,5390	0,6920	0,8280	0,9730
	1,55	0,0810	0,2350	0,3980	0,5420	0,6940	0,8290	0,9740
	1,65	0,0880	0,2410	0,4020	0,5440	0,6960	0,8300	0,9740
	1,75	0,0960	0,2460	0,4060	0,5470	0,6970	0,8310	0,9740
	1,85	0,1020	0,2510	0,4100	0,5500	0,6990	0,8320	0,9740
	1,95	0,1080	0,2560	0,4130	0,5520	0,7000	0,8320	0,9740
	2,05	0,1140	0,2610	0,4160	0,5550	0,7020	0,8330	0,9740
	2,15	0,1200	0,2650	0,4200	0,5570	0,7040	0,8340	0,9740
	2,25	0,1250	0,2690	0,4230	0,5590	0,7050	0,8350	0,9740
MH day-light ~	2,35	0,1300	0,2730	0,4260	0,5620	0,7060	0,8360	0,9750
	2,45	0,1350	0,2770	0,4290	0,5640	0,7080	0,8360	0,9750
	2,55	0,1390	0,2810	0,4320	0,5660	0,7090	0,8370	0,9750
	2,65	0,1440	0,2840	0,4340	0,5680	0,7110	0,8380	0,9750
	2,75	0,1480	0,2880	0,4370	0,5700	0,7120	0,8390	0,9750

b

	L_{mes} S/P	Photopic luminance cd·m^{-2} 0,01	0,03	0,1	0,3	1	3	10
LPS ~	0,25	0,0025	0,0075	0,0640	0,2340	0,8740	2,8100	9,9100
	0,35	0,0035	0,0136	0,0700	0,2430	0,8920	2,8400	9,9300
	0,45	0,0045	0,0173	0,0750	0,2530	0,9100	2,8600	9,9400
HPS ~	0,55	0,0055	0,0202	0,0800	0,2620	0,9270	2,8900	9,9500
	0,65	0,0065	0,0227	0,0850	0,2710	0,9430	2,9100	9,9600
	0,75	0,0075	0,0250	0,0890	0,2790	0,9600	2,9400	9,9700
	0,85	0,0085	0,0271	0,0940	0,2880	0,9760	2,9600	9,9800
	0,95	0,0095	0,0291	0,0980	0,2960	0,9920	2,9900	9,9900
	1,05	0,0105	0,0309	0,1020	0,3040	1,0080	3,0100	10,0100
MH warm white ~	1,15	0,0114	0,0327	0,1060	0,3120	1,0230	3,0400	10,0200
	1,25	0,0122	0,0345	0,1100	0,3200	1,0380	3,0600	10,0300
	1,35	0,0130	0,0361	0,1140	0,3270	1,0530	3,0800	10,0400
	1,45	0,0138	0,0378	0,1170	0,3350	1,0680	3,1000	10,0500
	1,55	0,0145	0,0394	0,1210	0,3420	1,0830	3,1300	10,0600
	1,65	0,0152	0,0409	0,1240	0,3490	1,0970	3,1500	10,0700
	1,75	0,0159	0,0424	0,1280	0,3560	1,1110	3,1700	10,0800
	1,85	0,0166	0,0439	0,1310	0,3630	1,1250	3,1900	10,0900
	1,95	0,0173	0,0454	0,1350	0,3700	1,1390	3,2100	10,1000
	2,05	0,0179	0,0468	0,1380	0,3770	1,1530	3,2300	10,1100
	2,15	0,0186	0,0482	0,1410	0,3840	1,1670	3,2600	10,1200
	2,25	0,0192	0,0496	0,1440	0,3900	1,1800	3,2800	10,1300
MH day-light ~	2,35	0,0198	0,0509	0,1470	0,3970	1,1930	3,3000	10,1400
	2,45	0,0205	0,0523	0,1510	0,4030	1,2060	3,3200	10,1500
	2,55	0,0211	0,0536	0,1540	0,4100	1,2190	3,3400	10,1600
	2,65	0,0216	0,0549	0,1570	0,4160	1,2320	3,3600	10,1700
	2,75	0,0222	0,0562	0,1600	0,4220	1,2450	3,3800	10,1800

2.5.3. Intermediate System

Although the USP- and MOVE-systems do show significant differences in the calculated mesopic luminance as a function of photopic luminance, particularly for highly coloured sources at low luminance levels, these differences become smaller at all levels for the majority of 'white light' sources used in typical lighting applications, such as roadway lighting at night. In practical terms, therefore, the results obtained using either of the two systems are similar. The principal difference between the systems lies in the form of the transition from the mesopic to photopic regimes. The USP-system has a transition from mesopic (mixed scotopic and photopic) functions to the single, photopic spectral luminous

efficiency function at 0.6 cd/m^2. The MOVE-system includes a contribution from the

scotopic spectral luminous efficiency function, albeit an ever-diminishing one, until about 10 cd/m2. The upper luminance limit of the mesopic region has been regarded to be too high for the MOVE-system (Rea and Bullough 2007) and too low for the USP-system (Eloholma and

Halonen 2006).

In some respects the USP- and MOVE-systems can be considered as representing two extremes. In the one case (USP), only reaction times were measured and chromatic effects were removed from consideration, with the result that this may limit the applicability to achromatic tasks only; in the other case (MOVE) a broad range of tasks is considered, but this introduces a greater degree of variability (or uncertainty) into the results, since the transition from the scotopic to the photopic condition is complicated by non-linear interactions between the chromatic and achromatic channels which may be different for each individual task. In the USP-system a small number (3) of observers were used to minimize 'noise' and in the MOVE-system a large number (119) of observers were used to minimize effects of inter-observer variability. It is also worth noting that although the MOVE- experiments included achromatic as well as chromatic tasks, the chromatic tasks dominated.

Real-life situations, such as driving on a road at night, involve both achromatic and chromatic tasks, and the achromatic tasks may be slightly under-weighted in the MOVE analysis.

An Intermediate system between the USP- and MOVE-systems was therefore also considered. This system was intended to ensure reasonably wide applicability while also giving increased weight to achromatic tasks as compared with the MOVE-system. Although being an Intermediate system, it is not an average of the USP- and MOVE-systems. There is a significant degree of freedom in the choice of the precise form of the transition and the following points have been considered in deciding this:

- It is advantageous, in terms of practical implementation of a new system of photometry, for there to be a definite upper and lower limit above and below which no change to the current system of photometry is necessary. This makes it clear, for example, whether a particular lighting specification standard needs to be changed to refer to the new system and avoids complicating unnecessarily general lighting applications where peripheral vision plays a less significant role. (It has been shown that V(λ) applies at all levels for tasks involving foveal vision only.)

- Based on the argument that the different experimental conditions underlying the USP-system and the MOVE-system explain the difference between the luminance level for the photopic mesopic transition in the two systems, the transition point for the Intermediate-system would be expected to lie between the USP-system value of 0.6 cd/m2 and the MOVE-system value of 10 cd/m2. Two different upper limits for the Intermediate-system, 3 cd/m2 and 5 cd/m2, have therefore been considered in the report.

- A log-linear relationship between the mesopic luminance and the adaptation coefficient 'y' value was selected, since this provides a better match to the data gathered within the MOVE project than a linear-linear relationship of the form used in the USP-system, and therefore provides a better approximation to actual visual performance for a wider range of tasks.

The Intermediate system with upper and lower limits of 3 cd/m2 and 0.01 cd/m2 , respectively, is denoted as the MES1-system and takes the form:

$$M(m_1)V_{mes}(\lambda) = m_1 V(\lambda) + (1 - m_1)V'(\lambda) \tag{3.4}$$

where $M(m_1)$ is a normalizing function such that the mesopic spectral luminous efficiency function, $V_{mes}(\lambda)$, attains a maximum value of 1.

If $L_{mes} \geq 3.0$ cd/m^2 , then $m_1 = 1$ If $L_{mes} \leq 0.01$ cd/m^2 , then $m_1 = 0$
If 0.01 cd• m^{-2}<L_{mes}< 3.0 cd/m^2 then $m_1 = 0.404 \log L_{mes} + 0.807$ where L_{mes} is the mesopic luminance.

The coefficient m_1 and the mesopic luminance L_{mes} obtained using the MES1-system can be iteratively calculated as follows:

$m_{1,0} = 0.5$

$$L_{mes,n} = \frac{m_{1,(n-1)} L_p + (1 - m_{1,(n-1)}) L_s V'(\lambda_0)}{m_{1,(n-1)} + (1 - m_{1,(n-1)}) V'(\lambda_0)} \quad (3.5)$$

$$m_{1,n} = a + b\log10(L_{mes,n}) \quad \text{for } 0 \le m_{1,n} \le 1$$

Where Lp is the photopic luminance, Ls is the scotopic luminance, V'(λ0) = 683/1699 is the value of scotopic spectral sensitivity function at λ0 = 555 nm, a and b are parameters which have the values a = 0.807 and b = 0.404, and n is an iteration step

The values of m1 and Lmes given by the MES1-system as a function of photopic luminance and light source S/P-ratio are presented in Table2.7.

Table 2.7 a) The values ofm1given by the MES1-system as a function of photopic luminance and S/P-ratio, b) values of Lmes given by the MES1-system as a function of photopic luminance and S/P-ratio

a

	m_1	Photopic luminance cd·m^{-2}						
	S/P	0,01	0,03	0,1	0,3	1	2	3
LPS ~	0,25	0	0	0,3311	0,5611	0,7941	0,9244	1
	0,35	0	0,0283	0,3450	0,5667	0,7960	0,9250	1
	0,45	0	0,0894	0,3569	0,5719	0,7978	0,9256	1
HPS ~	0,55	0	0,1199	0,3673	0,5768	0,7996	0,9261	1
	0,65	0	0,1417	0,3766	0,5814	0,8013	0,9267	1
	0,75	0	0,1591	0,3849	0,5858	0,8030	0,9273	1
	0,85	0	0,1736	0,3926	0,5899	0,8046	0,9278	1
	0,95	0	0,1861	0,3997	0,5939	0,8062	0,9284	1
	1,05	0,0074	0,1971	0,4062	0,5976	0,8078	0,9289	1
MH warm white ~	1,15	0,0223	0,2070	0,4123	0,6012	0,8093	0,9294	1
	1,25	0,0352	0,2160	0,4181	0,6047	0,8107	0,9299	1
	1,35	0,0466	0,2243	0,4235	0,6080	0,8121	0,9304	1
	1,45	0,0569	0,2319	0,4286	0,6111	0,8135	0,9309	1
	1,55	0,0663	0,2390	0,4334	0,6142	0,8149	0,9314	1
	1,65	0,0749	0,2456	0,4381	0,6172	0,8162	0,9318	1
	1,75	0,0828	0,2518	0,4425	0,6200	0,8175	0,9323	1
	1,85	0,0902	0,2577	0,4467	0,6228	0,8188	0,9328	1
	1,95	0,0971	0,2632	0,4507	0,6254	0,8200	0,9332	1
	2,05	0,1036	0,2685	0,4546	0,6280	0,8212	0,9337	1
	2,15	0,1098	0,2735	0,4583	0,6305	0,8224	0,9341	1
	2,25	0,1156	0,2783	0,4619	0,6330	0,8236	0,9345	1
MH day-light ~	2,35	0,1211	0,2829	0,4653	0,6353	0,8247	0,9349	1
	2,45	0,1263	0,2873	0,4687	0,6376	0,8258	0,9354	1
	2,55	0,1314	0,2915	0,4719	0,6399	0,8269	0,9358	1
	2,65	0,1362	0,2956	0,4750	0,6421	0,8280	0,9362	1
	2,75	0,1408	0,2995	0,4781	0,6442	0,8291	0,9366	1
	2,85	0,1452	0,3033	0,4810	0,6463	0,8301	0,9370	1
	2,95	0,1494	0,3069	0,4838	0,6483	0,8311	0,9373	1

	L_{mes}	b						
		Photopic luminance cd·m^{-2}						
	S/P	0,01	0,03	0,1	0,3	1	2	3
LPS ~	0,25	0,0025	0,0075	0,0664	0,2462	0,9292	1,9522	3
	0,35	0,0035	0,0118	0,0719	0,2541	0,9393	1,9590	3
	0,45	0,0045	0,0167	0,0769	0,2618	0,9492	1,9656	3
HPS ~	0,55	0,0055	0,0199	0,0816	0,2692	0,9588	1,9720	3
	0,65	0,0065	0,0226	0,0860	0,2764	0,9683	1,9784	3
	0,75	0,0075	0,0249	0,0902	0,2834	0,9776	1,9847	3
	0,85	0,0085	0,0270	0,0942	0,2902	0,9867	1,9909	3
	0,95	0,0095	0,0290	0,0981	0,2968	0,9956	1,9970	3
	1,05	0,0105	0,0309	0,1019	0,3032	1,0044	2,0030	3
MH warm white ~	1,15	0,0114	0,0327	0,1055	0,3095	1,0130	2,0089	3
	1,25	0,0123	0,0344	0,1090	0,3156	1,0215	2,0147	3
	1,35	0,0131	0,0361	0,1124	0,3216	1,0298	2,0204	3
	1,45	0,0139	0,0377	0,1157	0,3275	1,0380	2,0261	3
	1,55	0,0147	0,0393	0,1189	0,3333	1,0460	2,0316	3
	1,65	0,0154	0,0408	0,1221	0,3389	1,0540	2,0371	3
	1,75	0,0161	0,0422	0,1252	0,3445	1,0618	2,0425	3
	1,85	0,0168	0,0437	0,1283	0,3499	1,0694	2,0479	3
	1,95	0,0175	0,0451	0,1312	0,3553	1,0770	2,0531	3
	2,05	0,0182	0,0465	0,1342	0,3606	1,0845	2,0583	3
	2,15	0,0188	0,0478	0,1370	0,3658	1,0918	2,0634	3
	2,25	0,0194	0,0491	0,1399	0,3709	1,0991	2,0685	3
MH day-light ~	2,35	0,0201	0,0504	0,1427	0,3759	1,1063	2,0735	3
	2,45	0,0207	0,0517	0,1454	0,3809	1,1133	2,0784	3
	2,55	0,0213	0,0530	0,1481	0,3858	1,1203	2,0832	3
	2,65	0,0219	0,0542	0,1508	0,3906	1,1272	2,0880	3
	2,75	0,0224	0,0554	0,1534	0,3954	1,1340	2,0928	3
	2,85	0,0230	0,0566	0,1560	0,4001	1,1407	2,0974	3
	2,95	0,0236	0,0578	0,1585	0,4047	1,1473	2,1021	3

The Intermediate system with upper and lower limits of 5 cd/m^2 and 0.005 cd/m^2, respectively, is denoted as the MES2-system and takes the form:

$$M(m_2)V_{mes}(\lambda)=m_2V(\lambda)+(1-m_2)V'(\lambda) \qquad (3.6)$$

Where $M(m_2)$ is a normalizing function such that the mesopic spectral luminous efficiency function, $V_{mes}(\lambda)$, attains a maximum value of 1.

If $L_{mes} \geq 5.0$ cd/m^2, then $m_2 = 1$

If $L_{mes} \leq 0.005$ cd/m^2, then $m_2 = 0$

If 0.005 cd·m^{-2}<L_{mes}< 5.0 cd/m^2 , then $m_2 = 0.3334 \log L_{mes} +$

0.767 Where L_{mes} is the mesopic luminance .

The coefficient m_2 and the mesopic luminance L_{mes} obtained using the MES2-system can be iteratively calculated as follows:

$m_{2,0} = 0.5$

$$L_{mes,n} = \frac{m_{2,(n-1)}L_p + (1-m_{2,(n-1)})L_sV'(\lambda_0)}{m_{2,(n-1)} + (1-m_{2,(n-1)})V'(\lambda_0)} \qquad (3.7)$$

$$m_{2,n} = a + b\log 10(L_{mes,n}) \quad \text{for} \quad 0 \le m_{2,n} \le 1$$

Where L_p is the photopic luminance, L_s is the scotopic luminance, and $V'(\lambda_0) = 683/1699$ is the value of scotopic spectral sensitivity function at $\lambda_0 = 555$ nm, a and b are parameters which have the values a = 0.7670 and b = 0.3334, and n is an iteration step.

The values of m_2 and L_{mes} given by the MES2-system as a function of photopic luminance and light source S/P-ratio are presented in Table2.8.

Table 2.8 a) The values of m2given by the MES2-system as a function of photopic luminance and S/P-ratio, b) values of Lmes given by the MES2-system as a function of photopic luminance and S/P-ratio. (At photopic luminances of 5 cd/m2 the coefficient m2 has a value of 1 and the mesopic luminance is therefore 5 cd/m2, thus the photopic luminance 4.5 cd/m2 is more informative and is given in the Table 2.8)

a

	m_2	Photopic luminance cd·m^{-2}						
	S/P	0,01	0,03	0,1	0,3	1	3	4,5
LPS ~	0,25		0,1542	0,3830	0,5644	0,7538	0,9225	0,9841
	0,35		0,1804	0,3920	0,5688	0,7558	0,9230	0,9842
	0,45	0,0000	0,1992	0,4000	0,5730	0,7576	0,9235	0,9843
HPS ~	0,55	0,0190	0,2140	0,4073	0,5770	0,7594	0,9240	0,9844
	0,65	0,0459	0,2265	0,4139	0,5808	0,7612	0,9245	0,9845
	0,75	0,0655	0,2373	0,4201	0,5844	0,7629	0,9249	0,9846
	0,85	0,0812	0,2468	0,4258	0,5878	0,7646	0,9254	0,9846
	0,95	0,0943	0,2553	0,4311	0,5911	0,7662	0,9258	0,9847
	1,05	0,1057	0,2631	0,4361	0,5942	0,7678	0,9263	0,9848
MH warm white ~	1,15	0,1157	0,2702	0,4408	0,5972	0,7693	0,9267	0,9849
	1,25	0,1247	0,2767	0,4452	0,6001	0,7708	0,9272	0,9850
	1,35	0,1329	0,2828	0,4494	0,6029	0,7723	0,9276	0,9851
	1,45	0,1404	0,2885	0,4534	0,6056	0,7737	0,9280	0,9852
	1,55	0,1473	0,2939	0,4573	0,6082	0,7751	0,9284	0,9853
	1,65	0,1538	0,2990	0,4609	0,6107	0,7764	0,9289	0,9853
	1,75	0,1598	0,3038	0,4645	0,6131	0,7778	0,9293	0,9854
	1,85	0,1654	0,3083	0,4678	0,6155	0,7791	0,9297	0,9855
	1,95	0,1708	0,3126	0,4711	0,6178	0,7803	0,9301	0,9856
	2,05	0,1758	0,3168	0,4742	0,6200	0,7816	0,9304	0,9857
	2,15	0,1806	0,3207	0,4772	0,6221	0,7828	0,9308	0,9857
	2,25	0,1852	0,3245	0,4801	0,6242	0,7840	0,9312	0,9858
MH day-light ~	2,35	0,1895	0,3282	0,4830	0,6263	0,7852	0,9316	0,9859
	2,45	0,1937	0,3317	0,4857	0,6283	0,7863	0,9319	0,9860
	2,55	0,1977	0,3351	0,4883	0,6302	0,7875	0,9323	0,9860
	2,65	0,2015	0,3383	0,4909	0,6321	0,7886	0,9327	0,9861
	2,75	0,2052	0,3415	0,4934	0,6339	0,7896	0,9330	0,9862

b

L_{mes} — Photopic luminance cd·m^{-2}

	S/P	0,01	0,03	0,1	0,3	1	3	4,5
LPS ~	0,25	0,0025	0,0145	0,0705	0,2467	0,9130	2,9265	4,4782
	0,35	0,0035	0,0174	0,0750	0,2545	0,9253	2,9367	4,4812
	0,45	0,0045	0,0198	0,0793	0,2620	0,9373	2,9468	4,4842
HPS ~	0,55	0,0057	0,0220	0,0834	0,2693	0,9492	2,9568	4,4872
	0,65	0,0069	0,0239	0,0873	0,2764	0,9608	2,9666	4,4901
	0,75	0,0079	0,0258	0,0911	0,2833	0,9722	2,9763	4,4929
	0,85	0,0088	0,0275	0,0947	0,2901	0,9835	2,9859	4,4958
	0,95	0,0096	0,0292	0,0983	0,2967	0,9945	2,9953	4,4986
	1,05	0,0104	0,0308	0,1017	0,3032	1,0054	3,0046	4,5014
MH warm white ~	1,15	0,0111	0,0323	0,1051	0,3096	1,0161	3,0139	4,5041
	1,25	0,0118	0,0338	0,1083	0,3158	1,0267	3,0230	4,5068
	1,35	0,0125	0,0353	0,1115	0,3220	1,0371	3,0319	4,5095
	1,45	0,0132	0,0367	0,1147	0,3280	1,0473	3,0408	4,5122
	1,55	0,0138	0,0381	0,1178	0,3339	1,0575	3,0496	4,5148
	1,65	0,0145	0,0395	0,1208	0,3398	1,0674	3,0582	4,5174
	1,75	0,0151	0,0408	0,1238	0,3455	1,0773	3,0668	4,5200
	1,85	0,0157	0,0421	0,1267	0,3512	1,0870	3,0753	4,5225
	1,95	0,0163	0,0434	0,1295	0,3568	1,0966	3,0836	4,5250
	2,05	0,0169	0,0446	0,1324	0,3623	1,1060	3,0919	4,5275
	2,15	0,0174	0,0459	0,1352	0,3677	1,1154	3,1001	4,5299
	2,25	0,0180	0,0471	0,1379	0,3731	1,1246	3,1082	4,5323
MH day-light ~	2,35	0,0185	0,0483	0,1406	0,3784	1,1338	3,1162	4,5347
	2,45	0,0191	0,0495	0,1433	0,3836	1,1428	3,1241	4,5371
	2,55	0,0196	0,0506	0,1459	0,3888	1,1517	3,1319	4,5395
	2,65	0,0201	0,0518	0,1485	0,3939	1,1605	3,1396	4,5418
	2,75	0,0207	0,0529	0,1511	0,3989	1,1693	3,1473	4,5441

2.6 APPLICATION OF MESOPIC SYSTEM

Mesopic photometry provides the means to compare light sources at low levels using a common criterion. It is foreseen that there will be a strong motivation within the lighting community to adopt and use a photometric method that is valid and justified in the mesopic applications.

The mesopic design will provide means to optimize outdoor lighting both in terms of human visual performance and energy use. The use of mesopic photometry will promote the development of mesopically optimized lighting products. It will give the manufacturers foundations on which to develop light sources that are optimized for low light level applications. This will result in better energy efficiency and visual effectiveness in outdoor lighting conditions.

2.7 CALCULATION OF MESOPIC LUMINANCE

For the calculation of the mesopic luminance, the S/P ratio of the light source is needed. The higher the S/P ratio, the higher is the luminous efficacy of the light source in terms of mesopic design.

Table 2.9 shows the difference between the luminance values calculated using the recommended mesopic system and those calculated with the photopic spectral luminous efficiency function, for light sources with a range of S/P ratio values. Differences higher than 5% are highlighted in colour.

Table 2.9 Differences between mesopic and photopic luminances (%) calculated with the USP-, MOVE- and Intermediate (MES1 and MES2) systems for different photopic luminances Lp and light source S/P-ratio

	L_p / S/P	USP 0,01	0,03	0,1	L_p 0,3	$cd \cdot m^{-2}$ 1
LPS ~	0,25	-75 %	-73 %	-65 %	-34 %	0 %
	0,45	-54 %	-62 %	-44 %	-21 %	0 %
HPS ~	0,65	-34 %	-32 %	-26 %	-12 %	0 %
	0,85	-15 %	-14 %	-11 %	-5 %	0 %
	1,05	5 %	4 %	3 %	1 %	0 %
MH warm	1,25	24 %	22 %	16 %	7 %	0 %
white ~	1,45	43 %	38 %	27 %	11 %	0 %
	1,65	61 %	54 %	37 %	15 %	0 %
	1,85	79 %	69 %	47 %	18 %	0 %
	2,05	97 %	84 %	56 %	22 %	0 %
MH day-	2,25	115 %	98 %	65 %	25 %	0 %
light ~	2,45	132 %	112 %	73 %	27 %	0 %
	2,65	149 %	122 %	80 %	30 %	0 %

	Lp / S/P	0,01	0,03	MOVE 0,1	0,3	1	2	3	L_p 5	$cd \cdot m^{-2}$ 10
LPS ~	0,25	-75 %	-75 %	-36 %	-22 %	-13 %	-8 %	-6 %	-4 %	-1 %
	0,45	-55 %	-42 %	-25 %	-16 %	-9 %	-6 %	-5 %	-3 %	-1 %
HPS ~	0,65	-35 %	-24 %	-15 %	-10 %	-6 %	-4 %	-3 %	-2 %	0 %
	0,85	-15 %	-10 %	-6 %	-4 %	-2 %	-2 %	-1 %	-1 %	0 %
	1,05	5 %	3 %	2 %	1 %	1 %	1 %	0 %	0 %	0 %
MH warm	1,25	22 %	15 %	10 %	7 %	4 %	3 %	2 %	1 %	0 %
white ~	1,45	38 %	26 %	17 %	12 %	7 %	5 %	3 %	2 %	1 %
	1,65	52 %	36 %	24 %	16 %	10 %	7 %	5 %	3 %	1 %
	1,85	66 %	46 %	31 %	21 %	13 %	9 %	6 %	4 %	1 %
	2,05	79 %	56 %	38 %	26 %	15 %	12 %	8 %	5 %	1 %
MH day-	2,25	92 %	65 %	44 %	30 %	18 %	12 %	9 %	6 %	1 %
light ~	2,45	105 %	74 %	51 %	34 %	21 %	14 %	11 %	7 %	2 %
	2,65	116 %	83 %	57 %	39 %	23 %	16 %	12 %	7 %	2 %

	Lp / S/P	MES1					L_p	$cd \cdot m^{-2}$
		0,01	0,03	0,1	0,3	1	2	3
LPS ~	0,25	-75 %	-75 %	-34 %	-18 %	-7 %	-2 %	0 %
	0,45	-55 %	-44 %	-23 %	-13 %	-5 %	-2 %	0 %
HPS ~	0,65	-35 %	-25 %	-14 %	-8 %	-3 %	-1 %	0 %
	0,85	-15 %	-10 %	-6 %	-3 %	-1 %	0 %	0 %
	1,05	5 %	3 %	2 %	1 %	0 %	0 %	0 %
MH warm	1,25	23 %	15 %	9 %	5 %	2 %	1 %	0 %
white ~	1,45	39 %	26 %	16 %	9 %	4 %	1 %	0 %
	1,65	54 %	36 %	22 %	13 %	5 %	2 %	0 %
	1,85	68 %	46 %	28 %	17 %	7 %	2 %	0 %
	2,05	82 %	55 %	34 %	20 %	8 %	3 %	0 %
MH day-	2,25	94 %	64 %	40 %	24 %	10 %	3 %	0 %
light ~	2,45	107 %	72 %	45 %	27 %	11 %	4 %	0 %
	2,65	119 %	81 %	51 %	30 %	13 %	4 %	0 %

	Lp / S/P	MES2						L_p	$cd \cdot m^{-2}$
		0,01	0,03	0,1	0,3	1	2	3	5
LPS ~	0,25	-75 %	-52 %	-29 %	-18 %	-9 %	-5 %	-2 %	0 %
	0,45	-55 %	-34 %	-21 %	-13 %	-6 %	-3 %	-2 %	0 %
HPS ~	0,65	-31 %	-20 %	-13 %	-8 %	-4 %	-2 %	-1 %	0 %
	0,85	-12 %	-8 %	-5 %	-3 %	-2 %	-1 %	0 %	0 %
	1,05	4 %	3 %	2 %	1 %	1 %	0 %	0 %	0 %
MH warm	1,25	18 %	13 %	8 %	5 %	3 %	1 %	1 %	0 %
white ~	1,45	32 %	22 %	15 %	9 %	5 %	3 %	1 %	0 %
	1,65	45 %	32 %	21 %	13 %	7 %	4 %	2 %	0 %
	1,85	57 %	40 %	27 %	17 %	9 %	5 %	3 %	0 %
	2,05	69 %	49 %	32 %	21 %	11 %	6 %	3 %	0 %
MH day-	2,25	80 %	57 %	38 %	24 %	12 %	7 %	4 %	0 %
light ~	2,45	91 %	65 %	43 %	28 %	14 %	8 %	4 %	0 %
	2,65	101 %	73 %	49 %	31 %	16 %	9 %	5 %	0 %

The MES-2 table shows that lamps with a relatively high output in short wavelength region (S/P ratio>1) result in the increased luminance values when measured using the recommended system, whereas lamps using with relatively high output in the long wavelength region result in the decreased luminance values. The impact of using the recommended system increases with the decreasing light level. Currently recommended road surface luminances, which are within the range 0.3cd/m2 to 2 cd/m2 [CEN, 2003], [CIE, 1995], [Rea 2000], are indicated with a rectangle in the table. Many of the white light sources currently used for the applications such as road lighting have S/P ratios between about 0.65 (high pressure sodium) and 2.50 (certain metal halides).

2.8 COMPARISON OF LIGHT SOURCES

The use of mesopic dimensioning changes the luminous output and consequently the luminous efficacy orders of lamps.

Table 2.10 lists shows the S/P ratios of light sources used in outdoor lighting. Light sources with S/P>1 have higher content of their spectral output in the short wavelength region and are thus mesopically more efficient than light sources with S/P<1

Light source	R_{sp}
Low pressure sodium	0.23
High pressure sodium	0.4
Mercury vapour lamp	0.8
Incandescent	1.41
Quartz halogen	1.5
Fluorescent	1.5–2.4
Cool white LED	2.3
LED – red (635 nm)	0.06
LED – blue (470 nm)	14.3
LED – royal blue (450 nm)	28
Diode laser – red (650 nm)	0.016
Diode laser – blue (445 nm)	32

2.9 LIMITATIONS OF MESOPIC PHOTOMETRY

Although the mesopic photometry system is intended to predict visual task performance, it is not applicable to all tasks. There are some limitations due to simplification for modeling or limits of the underpinning visual evidences.

Firstly, the mesopic photometry system cannot be applied to tasks at all area on the retina. Since the density of the cones and the rods changes throughout the retina, and since the mesopic photometry system is based on visual tasks at eccentricity and more or less, visual task performances at the other retinal area may be different from those predicted by the system. The MOVE project chose the eccentricity because it is likely related to driving tasks. CIE 191 recommends to use the V (λ) function for foveal task performance prediction at all adaptation levels because the fovea is occupied only by the cones .

Secondly, it is not known whether it can be used for situations where observers are adapted to high-saturated colors. This is because the experiments underpinning the CIE 191 system mainly used white light, which closes to the black-body locus on the chromaticity diagram, for adaptation and background of the tasks. Applying the mesopic photometry system to extremely high-S/P-ratio sources should be avoided.

CHAPTER 3:

MESOPIC PHOTOMETRY IN OUTDOOR LIGHTINGAND CONCEPT OF ADAPTATION LUMINANCE

3.1 INTRODUCTION

The mesopic photometry recommended in CIE 191:2010 defines mesopic luminous efficiency functions, the spectral efficiency of which changes depending on the observer's adaptation luminance. Although the mesopic photometry system is expected to make outdoor lighting design more efficient and/or visually effective, there is still no international consensus about how the mesopic system should be implemented in real lighting applications. This is because of some technical issues. Of these issues, the absence of methods to determine the adaptation luminance for real lit scenes is the most critical.

An adaptation luminance for a lit scene has to be determined to obtain the mesopic luminous efficiency function that can predict task performances in the scene appropriately. The adaptation luminance should be determined on the basis of the peripheral adaptation state of observers' eyes since the mesopic photometry system was developed based on peripheral task performance [T Uchida et al.:2016].

3.1.1 Factors related to the adaptation luminance

It is difficult to determine an adaptation luminance for a real outdoor lit scene because scenes usually have complex luminance distributions (LDs), while laboratory experiments underpinning the mesopic photometry system were basically conducted with uniform LDs. The LDs for real lit scenes contain not only non-uniform lit road surfaces but also the dark sky or high-luminance sources such as luminaires. Their luminance ranges are extremely wide and to what luminance the observers' eyes adapt has been a big question.

Earlier studies have pointed out some factors that influence the adaptation state of observers. Here those factors are categorized into four types: LD, EMs, SLEs and AOM. To model the four factors and their derivatives as distribution functions in the field of view, two coordinate systems are introduced[TUchida et al.2016].One co-ordinate system is a spherical coordinate system (θ,φ) where θ is the horizontal angle and φ is the vertical angle, to basically present the position on the retina. This will be referred to as the 'retinal coordinate system'.

Another coordinate system is also a spherical coordinate system that has the same structure with different symbols (θ', φ'), but fixed to the world outside the observer, not to the observer's visual system. This will be referred as the 'object coordinate system'.
Both coordinate systems share the origin at the observer's eye position as shown in Figure 3.1.

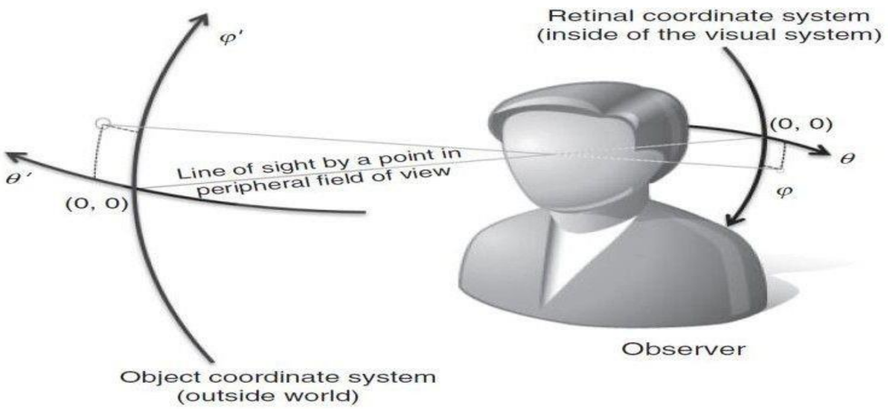


Fig 3.1 Object coordinate system and retinal coordinate system[T Uchida et al.2016]

When discussing the adaptation state of an arbitrary peripheral point in the field of view, the point $(\theta,\varphi)=(0,0)$ in the retinal coordinate system corresponds to a peripheral line of sight, the retinal coordinate system follows the movement while the object coordinate system does not.

3.1.1.1 Luminance distributions

The LD of a lit scene is a fundamental factor for the adaptation luminance. Usually, the luminance range for outdoor lighting at night is much wider than that for indoor lighting. According to outdoor lighting recommendations, such as CIE 115:2010, average luminance of 0.3 to 2.0 cd/m2is recommended. Since a certain level of non- uniformity is allowed in the recommendations, the minimum luminance, usually at the end of lit areas, may be 0.1 cd/m2. On the other hand, there may be various bright light sources, such as luminaires, headlamps of oncoming cars or luminous signs, in the same scene. For example, some luminaires have a luminance of more than 10,000 cd/m2. In this study, LD is expressed as a luminance level function $L(\theta',\varphi')$ with respect to the object coordinate system (θ',φ').

3.1.1.2 Surrounding luminance effect

The SLE is an increment of the adaptation luminance at a point in the field of view caused by the surrounding luminance. It is due to stray light within the human eye and/or lateral neural interactions. For foveal vision, this factor is called as 'veiling luminance' and has been investigated for many years. The angular characteristic, which is the luminance increment as a function of the visual angle between a source causing the veiling luminance and the task point (fovea), is modelled as some equations, such as Stiles-Holladay formula or CIE general disability glare equation. Since the mesopic photometry system is based on peripheral task performances, SLE for peripheral vision should be characterized and be taken into account.

3.1.1.3 Area of measurement

AOM is an area that is illuminated by a lighting installation and is measured photometrically to verify the installation. For example, a road surface that the lighting design intends to illuminate is the AOM. The road surface is usually seen as a trapezoidal area from the drivers' view point.
For the adaptation luminance simulation, AOM is modelled as a 2D function $f_{AOM}(\theta',\varphi')$ with respect to the object coordinate system (θ',φ'). This function takes a value of one for inside the AOM and zero for outside the AOM.[T Uchida et al.2016]

3.1.1.4 Eye movement

In a study[Uchida at el2016] , the Eye Movements are modelled as a two-dimensional (2D) Gaussian probability density distribution $f_{EM}(\theta',\varphi')$ with no correlation expressed as

$$f_{EM}(\theta',\varphi') = \frac{1}{2\pi\sigma_{\theta'}\sigma_{\varphi'}} * \exp[-\frac{1}{2}\{(\frac{\theta'}{\sigma_{\theta'}})^2 + (\frac{\varphi'}{\sigma_{\varphi'}})^2\}]d\theta' d\varphi' \quad (3.8)$$

Where $\sigma_{\theta'}$,,$\sigma_{\varphi'}$ are standard deviations (SD) for the horizontal and vertical directions. This function is defined with respect to the object coordinate system. It should be noted that the EM function is centred at the origin of the object coordinate system so that it just expresses relative movement of the line of sight.[T Uchida et al.2016]

3.2 VISUAL ADAPTATION FIELD

The CIE defines the field of vision (equivalent term: visual field) as the ‘extent of space in which objects are visible to an eye in a given position. In the horizontal plane meridian the field of vision extends to nearly 190° with both eyes open, the area seen binocularly is about 120°, and the area seen by one eye only is about 154°.

The society of Automotive Engineers (SAE), an organization for engineering professionals in the aerospace, automotive, and commercial vehicle industries, has defined the field of view (visual field) as ‘the extent of visual space over which vision is possible with the eyes in a fixed position (i.e., while looking straight ahead, it is the entire region of space visible)’.

Adaptation is defined as the ‘process by which the state of the visual system is modified by previous and present exposure to stimuli that may have various luminance values, spectral distributions and angular substances. The state of adaptation is the ‘state of the visual system after an adaptation process has been completed’. The visual adaptation field depends on the lighting conditions, and the behaviour of road users in various driving and walking conditions [Wei LUO].

3.3 ADAPTATION LUMINANCE

Mainly in case of road-lighting conditions the luminance in the field of view is not uniform. For reasons of simplicity, the average road-surface luminance is often, wrongly, taken as the adaptation luminance. Many other, often high-value, luminances in the visual field play a role. Think of the bright road-lighting luminaires, the headlamps of oncoming cars, luminous signs and light reflected off various surfaces. All these will increase the adaptation luminance to a value higher than the average road- surface luminance. The shift of the spectrum towards small wavelengths is therefore smaller than would be concluded from the average road-surface luminance alone. How exactly the adaptation luminance has to be determined is the subject of investigations. In particular eye-tracking instrumentation is used to study eye viewing directions and fixation points. The purpose is to determine where the adaptation field is centered, what shape it has and what size it has. A Technical Committee of CIE (CIE JTC-1 “Implementation of CIE 191 mesopic photometry in outdoor lighting”) is coordinating this work. Once the adaptation field is known the next step is to determine how the different luminances in that field have to be weighted. The effect of glare sources in the adaptation field can be roughly estimated by their veiling luminance [Uchida and Ohno 2013].

3.4 DIFFERENCE BETWEEN PHOTOPIC , MESOPIC AND ADAPTATION LUMINANCE

Photopic Luminance (L_p) is related to photopic photometry. It can be measured directly by Luminance meter. In accordance with the CIE 191 recommended system for mesopic photometry, the mesopic spectral luminous efficiency function $V_{mes}(\lambda)$ is calculated as a linear combination of the photopic spectral luminous efficiency function V (λ) and the scotopic spectral luminous efficiency function V (λ) as

$$V_{mes}(\lambda) = \frac{1}{M(m)}[mV(\lambda) + (1-m)V'(\lambda)] \qquad (3.9)$$

where $0 \leq m \leq 1$ is the adaptation level of the observer and M(m) is the normalization function, such that $V_{mes}(\lambda)$ attains a maximum value of 1. Mesopic luminance L_{mes} is obtained by weighting the spectral radiance $L_e(\lambda)$ with the mesopic luminous efficiency function $V_{mes}(\lambda)$ and by integrating over the visible wavelength range

$$L_{mes} = \frac{K_{cd}}{V_{mes}(\lambda_0)} \int V_{mes}(\lambda) L_e(\lambda) d\lambda \qquad (3.10)$$

where λ_0 555.016nm is the wavelength in standard air at which the SI unit of candela is defined and K_{cd}=683 lm/W is the luminous efficacy of monochromatic radiation at λ_0.

Combining both equations, the Mesopic luminance L_{mes} can be expressed as a weighted sum of the photopic luminance L_p and the scotopic luminance L_s.

$$L_{mes} = \frac{mL_p + (1-m)L_s V'(\lambda_0)}{m + (1-m)V'(\lambda_0)} \qquad (3.11)$$

where $V'(\lambda_0)$ 0.40175 is the value of the scotopic luminous efficiency functions at λ_0.
And Adaptation Luminance(L_a) can be predicted by the equation

$$L_a = L_{local} + L_{veil} \qquad (3.12)$$

where L_{local} can be determined from photopic luminance of the light source.

L_{veil} can be determined from various equations like-

1. Stiles–Holladay formula[Ohno 2015]

$$L_{veil} = \frac{10}{\theta^2} E \qquad (3.13)$$

where E is the vertical illuminance at the observer's eye due to a glare source, and θ is the visual angle (in degrees) between the glare source and the line of sight.

2. A general disability glare equation[Ohno 2015]

$$L_{veil} = \{\frac{10}{\theta^3} + [\frac{5}{\theta^2} + \frac{0.1p}{\theta}] * [1 + (\frac{A}{62.5})^4 + 0.0025p\}E \qquad (3.14)$$

where A is the age of the observer in years, p is the eye pigment factor, which ranges from 0 for black eyes to 1.2 for very light-blue eyes.

3. Stiles and Crawford model[Ohno 2015]

$$L_{veil} = \frac{16}{\theta^2} E_n$$

where E_n is the normal illuminance (on a plane perpendicular to the direction from the source) at the observer's eye due to a glare source and θ is visual angle (in degrees) between the glare source and a task point where the veiling luminance is caused.

4. Uchida &Ohno model[Ohno 2015]

L_{veil}

$$= \frac{260\ Ev}{\theta^3} \qquad (3.15)$$

where Ev is the vertical illuminance due to the SLE source. θ is the visual angle between the source and a task point in degrees.

CHAPTER 4:

COMPUTATIONAL SET UP

4.1 INTRODUCTION

This chapter describes the computational procedure for determination of photopic , mesopic and adaptation luminance of outdoor area. The objective of the thesis is to use an alternate avenue for calculation of the aforesaid luminance without using the experimental laboratory setup. For the analysis, a particular area of measurement of a road considered and is divided into 21x 7 grid points with the dimension of 1 m x 1 m .The length and width of the road are 20 meter and 6 meter respectively.

4.1.1 Specification of the luminaire

Two different sources of lights are considered with the following specification.

Main Source of Light	High Pressure Sodium Vapour lamp	Model : **PHILIPS SGS102 MR SON-TPP CONV**
Surrounding Source of Light	Fluorescent Lamp	Model: **PHILIPS TCS306/236 HF NORMAL**

4.2 THEORETICAL BACKGROUND

In this work, a 20 meter long and 6 meter wide road is considered for establishing the relationship between different parameters required to build the proposed model. A standard luminaire is considered to act as the street light. The schematic diagram of the overall system is depicted in Fig.4.1.

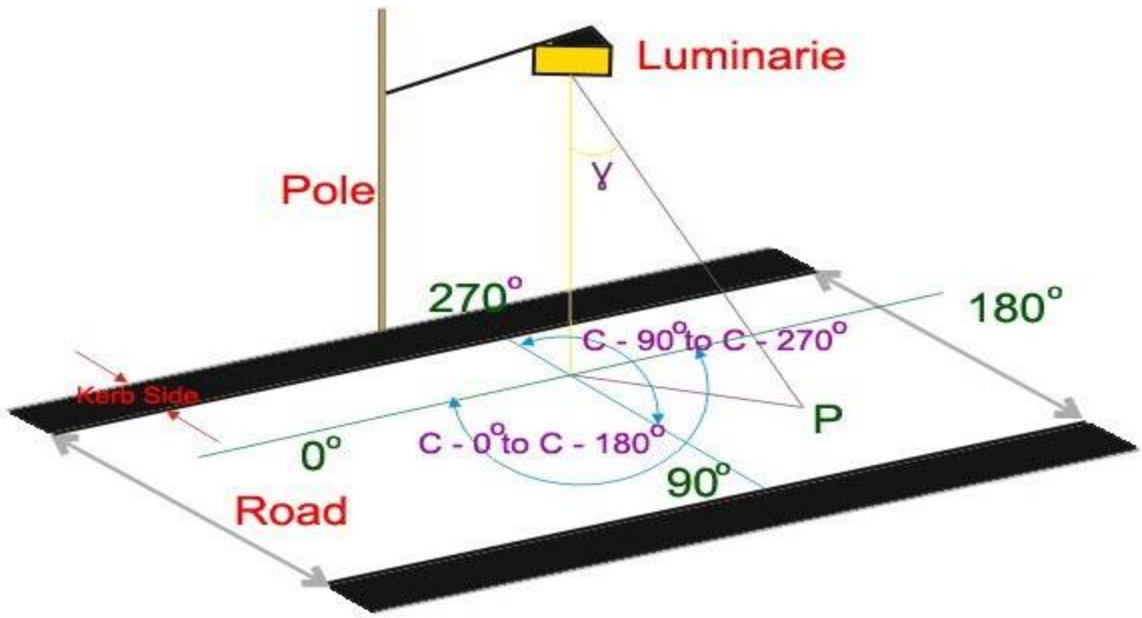


Fig.4.1. Schematic diagram of the overall system

4.2.1 Algorithm for determination of Photopic ,Mesopic and Adaptation Luminance

The detailed algorithm for calculating the photopic , mesopic and adaptation luminance is illustrated as given below:

Step 1: Luminous intensity values (I-table) for the area under measurement are calculated from the IES file of the luminaire.

Step 2: (C, γ) angle of all grid points under measurement area are calculated using "Interpolation Program" function in the MATLAB. Luminous intensity values are interpolated from the known I-table value for all grid points.

Step 3: The point specific illuminance (E) is calculated using the Inverse square law as given in (4.1).

$$E = \frac{I(C,\gamma)Cos^3\gamma}{{h_m}^2} \tag{4.1}$$

where, $I(C,\gamma)$ is the intensity at a particular (C,γ) angle , h_m is the pole mounting height.

Step 4: Reflectance value (ρ) of all grid points are calculated from R-table of the road surface.
Step 5: The theoretical photopic luminance (L_p) is determined using (4.2).

$$L_p = \rho E \tag{4.2}$$

Step 6: The point specific mesopic luminance values for all the grid points are calculated from the corresponding photopic luminance(L_p) using CIE191-2010 table as mentioned in Table 4.1. The mesopic luminance are computed from a given S/P ratio of a particular luminaire using interpolation

Table 4.1 L_{mes} **of the recommended mesopic system as a function of photopic luminance and S/P-ratio of light source**

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		Photopic luminance / cd·m^{-2}						
	S/P	**0,01**	**0,03**	**0,1**	**0,3**	**1**	**3**	**4,5**
LPS ~	**0,25**	0,002 5	0,014 5	0,070 5	0,246 7	0,913 0	2,926 5	4,478 2
	0,35	0,003 5	0,017 4	0,075 0	0,254 5	0,925 3	2,936 7	4,481 2
	0,45	0,004 5	0,019 8	0,079 3	0,262 0	0,937 3	2,946 8	4,484 2
HPS ~	**0,55**	0,005 7	0,022 0	0,083 4	0,269 3	0,949 2	2,956 8	4,487 2
	0,65	0,006 9	0,023 9	0,087 3	0,276 4	0,960 8	2,966 6	4,490 1
	0,75	0,007 9	0,025 8	0,091 1	0,283 3	0,972 2	2,976 3	4,492 9
	0,85	0,008 8	0,027 5	0,094 7	0,290 1	0,983 5	2,985 9	4,495 8
	0,95	0,009 6	0,029 2	0,098 3	0,296 7	0,994 5	2,995 3	4,498 6
	1,05	0,010 4	0,030 8	0,101 7	0,303 2	1,005 4	3,004 6	4,501 4
MH warm white ~	**1,15**	0,011 1	0,032 3	0,105 1	0,309 6	1,016 1	3,013 9	4,504 1
	1,25	0,011 8	0,033 8	0,108 3	0,315 8	1,026 7	3,023 0	4,506 8
	1,35	0,012 5	0,035 3	0,111 5	0,322 0	1,037 1	3,031 9	4,509 5
	1,45	0,013 2	0,036 7	0,114 7	0,328 0	1,047 3	3,040 8	4,512 2
	1,55	0,013 8	0,038 1	0,117 8	0,333 9	1,057 5	3,049 6	4,514 8
	1,65	0,014 5	0,039 5	0,120 8	0,339 8	1,067 4	3,058 2	4,517 4
	1,75	0,015 1	0,040 8	0,123 8	0,345 5	1,077 3	3,066 8	4,520 0
	1,85	0,015 7	0,042 1	0,126 7	0,351 2	1,087 0	3,075 3	4,522 5
	1,95	0,016 3	0,043 4	0,129 5	0,356 8	1,096 6	3,083 6	4,525 0
	2,05	0,016 9	0,044 6	0,132 4	0,362 3	1,106 0	3,091 9	4,527 5
	2,15	0,017 4	0,045 9	0,135 2	0,367 7	1,115 4	3,100 1	4,529 9
	2,25	0,018 0	0,047 1	0,137 9	0,373 1	1,124 6	3,108 2	4,532 3
MH daylight ~	**2,35**	0,018 5	0,048 3	0,140 6	0,378 4	1,133 8	3,116 2	4,534 7
	2,45	0,019 1	0,049 5	0,143 3	0,383 6	1,142 8	3,124 1	4,537 1
	2,55	0,019 6	0,050 6	0,145 9	0,388 8	1,151 7	3,131 9	4,539 5
	2,65	0,020 1	0,051 8	0,148 5	0,393 9	1,160 5	3,139 6	4,541 8
	2,75	0,020 7	0,052 9	0,151 1	0,398 9	1,169 3	3,147 3	4,544 1

.

Step 7: I-table of the luminaire obtained using IES file of the luminaire. Vertical illuminance (E_v) due to the surrounding light sources are thus computed from the I-table of the luminaire.

Step 8: The total E_v is computed for the three different FTL of surrounding light sources. Veiling luminance caused by the surrounding light sources has an impact on the adaptation luminance perceived by the observer. Veiling luminance is calculated by the (4.3)

$$L_{veil} = \frac{260}{\theta^3} Ev \qquad (4.3)$$

where, E_v is the vertical illuminance due to the surrounding light source ,θ is the visual angle between the main light source and any task point in degree.

Step 9:. The presence of surrounding lighting ambience significantly affects the effective adaptation luminance and adaptation Luminance(L_a) is determined using (4.4).

where, Local luminance (L_{local}) values are nothing but the photopic luminance values on the grid points for all individual sources and $L_{veil}$is the Veiling luminance.

$$L_a = L_{local} + L_{veil} \quad (4.4)$$

4.3 DETAIL DESCRIPTION OF THE LUMINAIRE

Two types of luminaires are used in this work . The model number of the luminaires are mentioned in the subsection 4.1.1.The detailed description of the luminaires are described below:

Main Source of Light:
Luminaire: PHILIPS SGS 102 MR SON –TPP CONV
Lamps: 1XSON-TPP 100W

Luminous flux (Luminaire): 7530 lm
Luminous flux (Lamps): 10700 lm
Luminaire Wattage: 114.0 W
Luminaire classification according to CIE: 100
CIE flux code: 47 81 97 100 70
Fitting: 1 x SON-TPP100W (Correction Factor 1.000).
The luminous emittance profile of PHILIPS SGS 102 MR SON –TPP CONV is depicted in Fig.4.2.

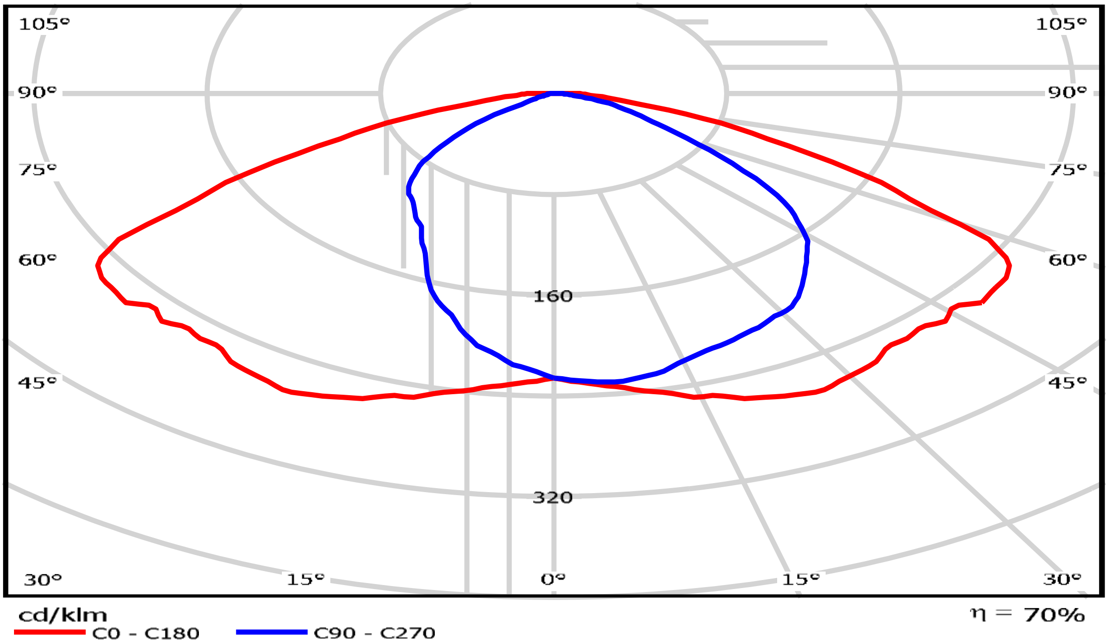

Fig.4.2. Luminous emittance profile of main source of light

Surrounding Source of Light:

Luminaire : PHILIPS TCS306/236 HF NORMAL
Luminous flux (Luminaire): 3858 lm
Luminous flux (Lamps): 6410 lm
Luminaire Wattage: 74.0 W
Luminaire classification according to CIE: 100
CIE flux code: 54 88 98 100 60
Fitting: 2 x TLD 36W (Correction Factor 1.000).

The luminous emittance profile of PHILIPS TCS306/236 HF NORMAL is depicted in Fig.4.3.

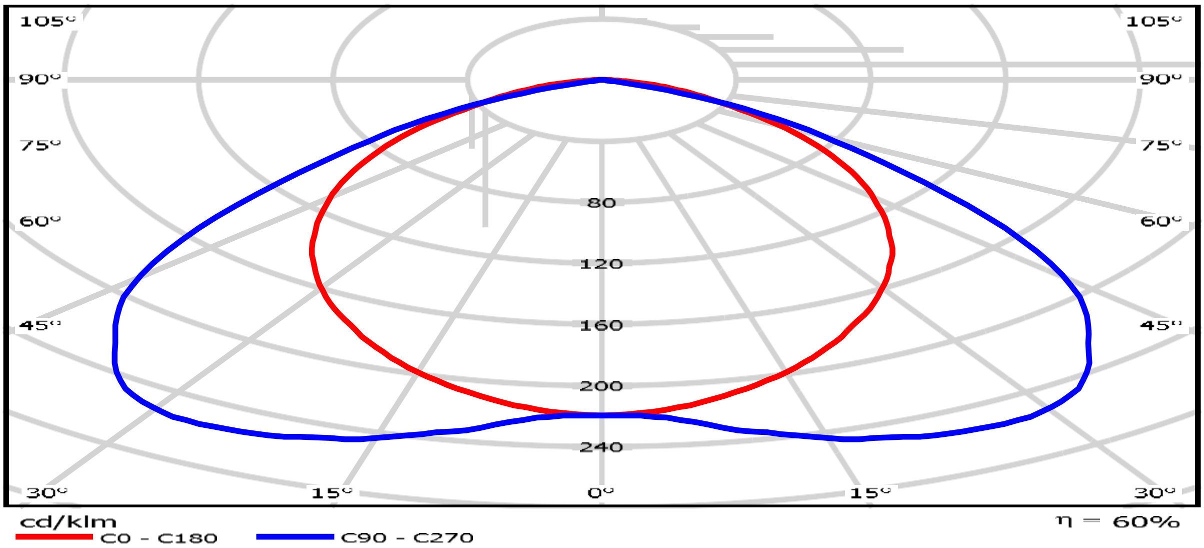

Fig.4.3. Luminuous emittance profile of surrounding source of light

4.4 DETERMINATION OF REFLECTION FACTOR (ρ)

For a precise designing of road/street lighting, the reflection properties of the road surface is required. The reflection properties of any road is represented by a reduced luminance coefficient table or commonly known as R-table. A standard R-table for dry road surfaces is shown in Fig. 4.5.

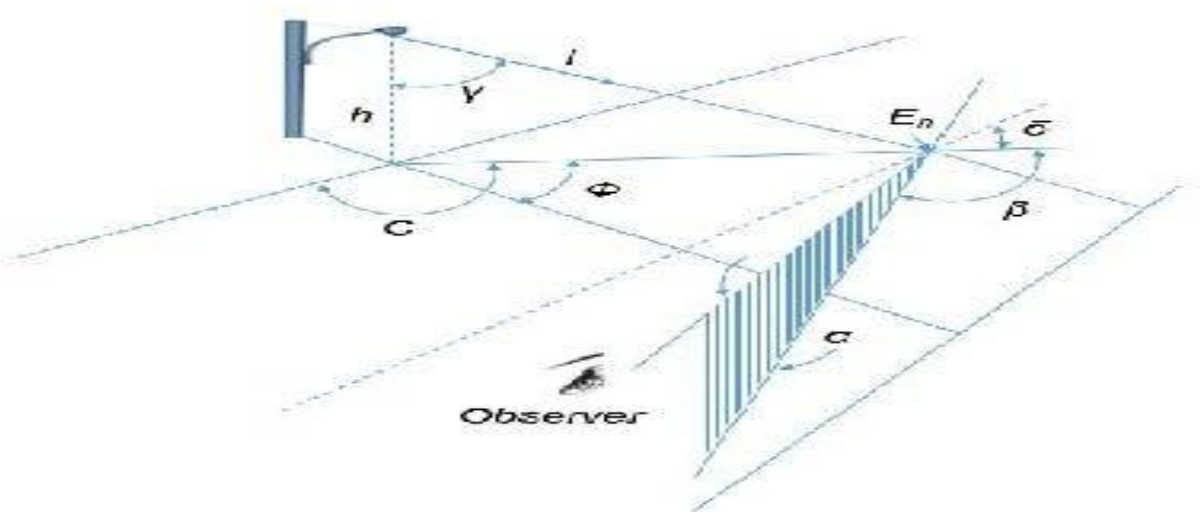

Fig.4.4. Schematic diagram for determination of reflection factor of road

Fig.4.4 is used to determine the road surface reflection properties and surface classification as defined in the CIE 66-1984 (CIE, 1984). The reflection properties of a road surface are described by a set of luminance coefficients which are dependent on the certain angles . The angles are shown in the Fig.4.4. Angle of incidence is denoted by which is the angle between the direction of incident light and the upward vertical position of the luminaire. The angle of observation is denoted by α , defined as the angle in a vertical plane, relative to the horizontal, at which the light is transmitted from the reflection point P to the observer's eyes. β is the angle of intersection defined as the angle in between of the vertical plane of incident light and the vertical plane of observation with considering point P as the intersection point and δ is the angle between the vertical plane of observation and the road axis. Since most road surfaces are almost completely isotropic, the influence of δ can be neglected.

ROADSURFACE STANDARD R1 (Q0 TABLE=1.00)

TAN (GAMMA) = R/H-VALUES CORRESPONDING TO THE LISTED NUMBERS OF REFLECTION VALUES

ETA I	0.0	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.50	3.00	3.50	4.00	4.50	5.00	5.50	6.00	6.50	7.00
EG. I	7.50	8.00	8.50	9.00	9.50	10.00	10.50	11.00	11.50	12.00									
0	6550	6190	5390	4310	3410	2690	2240	1890	1620	1210	940	810	710	630	570	510	470	430	400
	370	350	330	310	300	290	280	270	260	250									
2	6550	6190	5390	4310	3410	2690	2240	1890	1620	1210	940	800	690	590	520	470	420	380	340
	310	280	250	230	220	200	180	160	150	140									
5	6550	6190	5390	4310	3410	2690	2240	1890	1570	1170	860	660	550	430	360	310	250	220	180
	150	140	120	100	90	80	70	70	60	60									
10	6550	6190	5390	4310	3410	2600	2150	1710	1350	950	660	460	320	240	190	150	120	100	80
	70	60	50	40	40	30	30	30	20	20									
15	6550	6100	5390	4310	3230	2510	1980	1530	1170	790	490	330	230	170	140	110	90	70	60
	50	40	40	30	30	20	20	20	20	20									
20	6550	6100	5390	4310	3230	2420	1800	1390	1080	660	410	280	200	140	120	90	70	60	50
	40	40	30	30	30	20	20	20											
25	6550	6100	5210	4310	3050	2240	1710	1300	990	600	380	250	180	130	100	80	70	50	40
	40	30	30																
30	6550	6100	5210	4310	2960	2070	1620	1210	940	570	360	230	160	120	90	80	60	50	40
35	6550	6100	5210	4310	2870	1980	1530	1170	900	540	340	220	150	120	90	80	60		
40	6550	6100	5210	4310	2870	1890	1480	1120	850	520	330	220	140	110	90	80			
45	6550	6100	5210	3950	2780	1890	1440	1080	850	510	320	210	140	110	90				
60	6550	6100	5030	3860	2690	1800	1440	1030	830	500	310	210	140	110	90				
75	6550	6100	5030	3710	2690	1800	1390	990	840	510	310	220	150	120	90				
90	6550	6010	5030	3710	2690	1800	1390	990	840	520	330	220	170	130	100				
105	6550	6010	5030	3710	2690	1800	1390	1030	860	540	350	240	190	140	110				
120	6550	6010	5030	3710	2690	1800	1440	1080	900	580	380	270	200	140	130				
135	6550	6010	5030	3710	2690	1890	1480	1120	940	610	400	290	220	160	140				
150	6550	6010	5030	3860	2780	1980	1530	1210	990	650	430	310	230	170	150				
165	6550	6010	5030	3950	2780	2070	1620	1300	1030	690	470	340	250	190	160				
180	6550	6010	5030	3950	2780	2240	1800	1390	1110	750	510	380	270	210	160				

ALL VALUES ARE MULTIPLIED BY 10000

Standard Reflection Tables for Dry Road Surfaces (R and N-tables)

Fig.4.5. Standard reflection table for dry road surfaces

CHAPTER 5:

COMPUTATION

5.1 INTRODUCTION

In this chapter determination of illuminance ,photopic luminance , mesopic luminance and adaptation luminance are computed using IES files, I-table and interpolation algorithm in MATLAB .

5.1 .1 Determination of Illuminance (E)

A section of road is considered and a specific grid points are made on that area. The grid point dimension considered for this study is 7X21. Illuminance at each grid points are measured using the following steps.

Step1: Luminous Intensity values (I-Table) of the luminaire are computed from the IES files of the used luminaire .

Step2: (C,γ) angle of all grid points under measurement area are calculated using "Interpolation Program" function in the MATLAB. Luminous intensity values are interpolated from the known I- table value for all grid points.

The standard I-table for main light source (PHILIPS SGS 102 MR SON –TPP CONV) is demonstrated in Table 5.1.

Table 5.1 Luminous Intensity Table (I-table) for Main Light Source

c/γ	0	15	30	40	45	50	55	60
0	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2
2.5	2439.6	2439.6	2428.9	2450.3	2461	2461	2450.3	2450.3
5	2461	2461	2482.4	2503.8	2493.1	2482.4	2471.7	2482.4
7.5	2471	2471	2493.1	2525.2	2525.2	2546.6	2525.2	2535.9
10	2450.3	2461	2415.5	2535.9	2546.6	2568	2578.7	2589.4
12.5	2428.9	2407.5	2525.2	2568	2589.4	2610.8	2621.5	2664.3
15	2375.9	2428.9	2535.9	2578.7	2653.6	2664.3	2685.7	2664.3
17.5	2332.6	2428.9	2525.2	2621.5	2642.9	2653.6	2717.8	2670.7
20	2300.5	2375.4	2514.5	2610.8	2685.7	2707.1	2739.2	2749.9
22.5	2279.1	2343.3	2482.4	2621.5	2653.6	2707.1	2760.6	2803.4
25	2247	2321.9	2450.3	2568	2664.3	2717.8	2792.7	2835.5
27.5	2225.6	2279.1	2332.6	2557.3	2664.3	2728.5	2771.3	2835.5
30	2182.8	225.6	2279.1	2525.2	2610.8	2685.7	2771.3	2835.5
32.5	2172.1	2140	2214.9	2482.4	2546.6	2642.9	2728.5	2782

35	2107.9	2065.1	2161.4	2407.5	2514.5	2589.4	2642.9	2728.5
37.5	2022.3	2011.6	2065.1	2332.6	2418.2	2493.1	2589.4	2642.9
40	1936.7	1926	1968.8	2225.6	2321.9	2354	2482.4	2525.2
42.5	1851.1	1840.4	1883.2	2086.5	2150.7	2268.4	2354	2514.5
45	1776.2	1765.5	1744.1	1958.1	2033	2172.1	2300.5	2439.6
47.5	1647.8	1679.9	1594.3	1819	1926	2054.4	2225.6	2396.8
50	1530.1	1572.9	1476.6	1733.4	1840.4	1958.1	2193.5	2386.1
52.5	1369.6	1380.3	1358.9	1605	1765.5	1947.4	2140	2364.7
55	1144.9	1177	1241.2	1572.9	1712	1851.1	2000.9	2332.6
57.5	941.6	1027.2	1155.6	1444.5	1572.9	1786.9	1968.8	2225.6
60	759.7	920.2	1037.9	1348.2	1476.6	1658.5	1808.3	2107.9
62.5	599.2	813.2	952.3	1187.7	1326.8	1476.6	1722.7	1926
65	502.9	642	845.3	1048.6	1241.2	1369.6	1433.8	1562.2
67.5	428	524.3	642	973.7	941.6	995.1	1080.7	1219.8
70	342.4	406.6	449.4	631.3	695.5	695.5	684.8	791.8
72.5	299.6	310.3	267.5	342.4	342.4	449.4	588.5	674.1
75	224.7	214	224.7	310.3	331.7	395.9	449.4	524.3
77.5	149.8	171.2	181.9	267.5	278.2	288.9	353.1	406.6
80	96.3	139.1	139.1	192.6	203.3	235.4	256.8	270
82.5	85.6	117.7	96.3	139.1	128.4	128.4	149.8	171.2
85	53.5	74.9	74.9	96.3	96.3	96.3	117.7	128.4
87.5	42.8	42.8	53.5	74.9	74.9	74.9	85.6	107
90	42.8	53.5	53.5	64.2	74.9	64.2	74.9	85.6

c/γ	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**	**105**
0	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2
2.5	2450.3	2450.3	2461	2450.3	2461	2450.3	2450.3	2461	2450.3
5	2482.4	2493.1	2503.8	2493.1	2503.8	2482.4	2482.4	2450.3	2461

7.5	2514.5	2535.9	2525.2	2514.5	2535.9	2514.5	2503.8	2482.4	2482.4
10	2568	2578.7	2589.4	2589.4	2578.7	2568	2546.6	2525.2	2514.5
12.5	2653.6	2664.3	2642.9	2632.2	2632.2	2600.1	2589.4	2546.6	2546.6
15	2685.7	2696.4	2685.7	2685.7	2685.7	2675	2632.2	2621.5	2578.7
17.5	2749.9	2739.2	2749.9	2728.5	2717.8	2685.7	2685.7	2621.5	2578.7
20	2792.7	2792.7	2803.4	2792.7	2771.3	2760.6	2739.2	2664.3	2610.8
22.5	2856.9	2856.9	2867.6	2856.9	2824.8	2792.7	2728.5	2653.6	2600.1
25	2856.9	2856.9	2878.3	2899.7	2867.6	2824.8	2771.3	2685.7	2621.5
27.5	2889	2910.4	2931.8	2931.8	2910.4	2856.9	2771.3	2707.1	2632.2
30	2889	2889	2889	2889	2867.6	2824.8	2749.9	2685.7	2578.7
32.5	2824.8	2835.5	2878.3	2867.6	2867.6	2803.4	2728.5	2632.2	2525.2
35	2782	2835.5	2889	2878.3	2856.9	2782	2685.7	2578.7	2461
37.5	2696.4	2771.3	2814.1	2824.8	2792.7	2707.1	2610.8	2493.1	2354
40	2621.5	2739.2	2792.7	2856.9	2814.1	2717.8	2610.8	2439.6	2300.5
42.5	2589.4	2717.8	2792.7	2803.4	2782	2685.7	2578.7	2407.5	2193.5
45	2568	2664.3	2771.3	2835.5	2814.1	2739.2	2568	2364.7	2140
47.5	2568	2653.6	2760.6	2803.4	2792.7	2675	2535.9	2321.9	2107.9
50	2568	2664.3	2803.4	2899.7	2867.6	2760.6	2578.7	2300.5	2054.4
52.5	2568	2685.7	2835.5	2899.7	2856.9	2739.2	2546.6	2268.4	2022.3
55	2568	2696.4	2803.4	2867.6	2846.2	2728.5	2535.9	2225.6	1958.1

57.5	2503.8	2685.7	2792.7	2867.6	2814.1	2675	2471.7	2161.4	1893.9
60	2364.7	2568	2653.6	2707.1	2578.7	2482.4	2172.1	1968.8	1658.5
62.5	2107.9	2279.1	2172.1	2214.9	2118.6	2022.3	1797.6	1540.8	1284
65	1669.2	1829.7	1968.8	2000.9	1979.5	1786.9	1669.2	1412.4	1273.3
67.5	1369.6	1423.1	1476.6	1530.1	1487.3	1423.1	1230.5	1037.9	813.2
70	1005.8	1144.9	1251.9	1262.6	1198.4	1123.5	973.7	813.2	706.2
72.5	781.1	866.7	941.6	1005.8	973.7	909.5	781.1	652.7	513.6
75	577.8	674.1	781.1	791.8	759.7	674.1	588.5	481.5	428
77.5	470.8	481.5	524.3	513.6	513.6	460.1	406.6	331.7	267.5
80	288.9	310.3	353.1	374.5	363.8	342.4	288.9	256.8	214
82.5	192.6	214	267.5	299.6	278.2	256.8	224.7	192.6	171.2
85	139.1	149.8	203.3	214	214	181.9	181.9	149.8	128.4
87.5	107	128.4	160.5	181.9	171.2	149.8	117.7	117.7	85.6
90	85.6	96.3	139.1	149.8	139.1	117.7	96.3	85.6	74.9

c/γ	**115**	**120**	**125**	**130**	**135**	**140**	**150**	**165**	**180**
0	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2	2418.2
2.5	2428.9	2418.2	2428.9	2407.5	2396.8	2396.8	2396.8	2396.8	2354
5	2439.6	2418.2	2386.1	2396.8	2386.1	2386.1	2375.4	2354	2311.2
7.5	2450.3	2418.2	2407.5	2396.8	2375.4	2354	2311.2	2300.5	2225.6
10	2471.7	2428.9	2407.5	2375.4	2354	2332.6	2289.8	2236.3	2172.1
12.5	2471.7	2428.9	2396.8	2343.3	2321.9	2300.5	2236.3	2107.9	2075.8
15	2482.4	2396.8	2364.7	2332.6	2321.9	2257.7	2182.8	2054.4	1947.4
17.5	2503.8	2428.9	2354	2300.5	2247	2214.9	2075.8	1958.1	1872.5
20	2493.1	2396.8	2343.3	2289.8	2204.2	2065.1	1990.2	1808.3	1776.2
22.5	2482.4	2407.5	2321.9	2225.6	2182.8	2043.7	1872.5	1701.3	1637.1
25	2439.6	2386.1	2300.5	2172.1	2086.5	1968.8	1754.8	1572.9	1498
27.5	2450.3	2343.3	2225.6	2129.3	2011.6	1893.9	1637.1	1465.9	1412.4

30	2396.8	2311.2	2161.4	2054.4	1947.4	1786.9	1508.7	1380.3	1305.4
32.5	2300.5	2193.5	2054.4	1958.1	1851.1	1647.8	1358.9	1326.8	1262.6
35	2214.9	2033	1958.1	1840.4	1701.3	1551.5	1262.6	1294.7	1198.4
37.5	2086.5	1947.4	1808.3	1733.4	1519.4	1348.2	1016.5	1219.8	1144.9
40	1958.1	1819	1712	1583.6	1444.5	1230.5	909.5	1144.9	1112.8
42.5	1851.1	1712	1615.7	1465.9	1358.9	1134.2	609.9	1123.5	1059.3
45	1744.1	1572.9	1530.1	1358.9	1305.4	1155.6	545.7	1091.4	973.7
47.5	1647.8	1530.1	1401.7	1337.5	1251.9	1134.2	535	995.1	888.1
50	1605	1465.9	1326.8	1251.9	1251.9	1134.2	524.3	888.1	770.4
52.5	1583.6	1444.5	1294.7	1198.4	1198.4	1102.1	481.5	716.9	642
55	1519.4	1391	1273.3	1155.6	1166.3	1070	438.7	567.1	513.6
57.5	1455.2	1294.7	1209.1	1155.6	1059.3	995.1	417.3	460.1	385.2
60	1380.3	1273.3	1134.2	1027.2	952.3	856	374.5	385.2	181.9
62.5	1005.8	1037.9	963	866.7	781.1	706.2	321	299.6	117.7
65	920.2	823.9	802.5	674.1	599.2	513.6	267.5	256.8	85.6
67.5	631.3	642	674.1	599.2	502.9	385.2	246.1	139.1	53.5
70	599.2	513.6	460.1	417.3	353.1	299.6	181.9	96.3	53.5
72.5	374.5	299.6	321	278.2	235.4	214	149.8	53.5	32.1
75	278.2	224.7	214	181.9	160.5	160.5	96.3	42.8	32.1
77.5	235.4	181.9	149.8	139.1	117.7	117.7	96.3	32.1	21.4
80	160.5	139.1	117.7	107	96.3	107	74.9	32.1	32.1
82.5	117.7	117.7	107	74.9	74.9	74.9	64.2	32.1	0
85	96.3	74.9	74.9	64.2	53.5	53.5	42.8	32.1	0
87.5	85.6	64.2	64.2	53.5	42.8	53.5	32.1	21.4	0
90	64.2	42.8	42.8	32.1	42.8	42.8	42.8	0	0

The standard I-table for surrounding light source (TCS31/236 NORMAL [LAMP] TLD 36W) is demonstrated in Table 5.2 .

Table 5.2 Luminous Intensity Table (I-table) for Surrounding Light Source

C/γ	0	22.5	45	67.5	90
0	1287	1287	1287	1287	1287
2.5	1280.5	1280.5	1287	1287	1287
5	1274	1274	1280.5	1280.5	1287
7.5	1261	1261	1274	1287	1293.5
10	1241.5	1248	1267.5	1300	1313
12.5	1222	1228.5	1267.5	1332.5	1365
15	1196	1209	1274	1391	1436
17.5	1170	1189.5	1300	1462.5	1527.5
20	1144	1170	1332.5	1534	1618.5
22.5	1111.5	1150.5	1378	1605.5	1696.5
25	1079	1131	1417	1664	1768
27.5	1046.5	1118	1449.5	1709.5	1807
30	1007.5	1105	1475.5	1729	1826.5
32.5	968.5	1092	1488.5	1722.5	1820
35	923	1079	1488.5	1696.5	1787.5
37.5	884	1072.5	1469	1651	1742
40	838.5	1053	1436.5	1592.5	1664
42.5	793	1033.5	1384.5	1514.5	1573
45	741	1014	1319.5	1410.5	1443
47.5	695.5	981.5	1241.5	1280.5	1280.5
50	643.5	942.5	1150.5	1124.5	1118
52.5	591.5	897	1046.5	968.5	949
55	539.5	838.5	929.5	812.5	773.5
57.5	487.5	767	793	656.5	598
60	435.5	689	656.5	500.5	429
62.5	377	604.5	533	351	286

65	325	520	403	234	175.5
67.5	279.5	429	292.5	143	97.5
70	227.5	338	195	84.5	52
72.5	182	253.5	123.5	52	26
75	143	182	78	32.5	19.5
77.5	104	123.5	58.5	26	13
80	78	84.5	45.5	26	13
82.5	58.5	58.5	39	19.5	13
85	39	39	26	19.5	13
87.5	26	26	19	13	6.5
90	0	0	0	0	0

Step3: The illuminance (E) is computed by (4.1) using MATLAB.

The illuminance(E) at different grid points under targeted area are tabulated in Table 5.3.

MATLAB CODE for Calculation of E:

```
I=xlsread('table of son');
I;
[x,y]=meshgrid(0:1:20, 0:1:6);
points=[x(:),y(:)];
h=9.0000;
format short
d=((x-10).^2+(y-0).^2).^0.5;
l=((h^2+d.^2).^0.5);
cos_gamma=h./l;
gamma=acosd(cos_gamma)
sin_theta=((y-0)./d);
C=90-asind(sin_theta);
for i=1:1:size(C,1);
    for j=1:1:size(C,2);
        n=(size(C,2)+1)/2;
            C(1,n)=0;
```

```
    end
end
C
interpolated_I=interpolation(C,gamma,I);
E=(interpolated_I.*(cos_gamma.^3))/(h^2);
```

Table 5.3 Simulated values of Illuminance (E) using MATLAB

9.95	11.96	13.90	16.45	19.86	23.40	26.49	28.61	29.87	30.30	29.85	30.30	29.87	28.61	26.49	23.40	19.86	16.45	13.90	11.96	9.95
10.32	12.19	14.29	16.93	20.17	23.56	26.72	28.85	30.13	30.20	29.89	30.20	30.13	28.85	26.72	23.56	20.17	16.93	14.29	12.19	10.32
10.11	11.77	13.83	16.20	19.27	22.38	25.38	27.29	28.33	28.28	27.89	28.28	28.33	27.29	25.38	22.38	19.27	16.20	13.83	11.77	10.11
9.44	10.83	12.64	14.62	17.23	20.15	22.64	24.34	25.06	25.07	24.46	25.07	25.06	24.34	22.64	20.15	17.23	14.62	12.64	10.83	9.44
8.56	9.80	11.15	12.86	14.97	17.29	19.15	20.31	20.96	21.53	21.29	21.53	20.96	20.31	19.15	17.29	14.97	12.86	11.15	9.80	8.56
7.63	8.53	9.56	10.81	12.37	14.36	15.77	16.28	11.86	8.11	18.13	8.11	11.86	16.28	15.77	14.36	12.37	10.81	9.56	8.53	7.63
6.54	7.23	7.95	8.93	10.05	11.53	12.41	13.24	14.10	14.80	15.23	14.80	14.10	13.24	12.41	11.53	10.05	8.93	7.95	7.23	6.54

5.1.2 Determination of Vertical Illuminance (E_v)

Step 1: IES file of the luminaire is used to compute I-table of the luminaire. Vertical illuminance (E_v) due to the surrounding light sources are thus computed from the I-table of the luminaire .

Step 2: Three different FTL of surrounding light sources are considered for calculation of vertical illuminance . The illuminance of each of the three surrounding light sources are computed using MATLAB by the same algorithm as mentioned in section 5.1.1.

Step 3: The vertical illuminance (E_v) for all the grid points is computed by adding all three luminance obtained for three different FTLs, thereby expressed by (5.1).

$$E_v = E_1 + E_2 + E_3 \tag{5.1}$$

MATLAB CODE for Calculation of E_V:

```
I3=xlsread('table of tube light');
 I3;
[x,y]=meshgrid(0:1:20, 0:1:6);
points=[x(:),y(:)];
h=9.0000;
format short
```

```
d=((x-10).^2+(y-0).^2).^0.5;
l=((h^2+d.^2).^0.5);
cos_gamma=h./l;
gamma=acosd(cos_gamma);
sin_theta=((y-0)./d);
C=90-asind(sin_theta);
for i=1:1:size(C,1);
    for j=1:1:size(C,2);
        n=(size(C,2)+1)/2;
                C(1,n)=0;
    end
end
C;
interpolated_I3=interpolation(C,gamma,I3);
E3=(interpolated_I3.*(cos_gamma.^3))/(h^2)
I1=xlsread('table of tube light2');
  I1;
[x,y]=meshgrid(0:1:20, 0:1:6);
points=[x(:),y(:)];
h=9.0000;
format short
d=((x-10).^2+(y-0).^2).^0.5;
l=((h^2+d.^2).^0.5);
cos_gamma=h./l;
gamma=acosd(cos_gamma);
sin_theta=((y-0)./d);
C=90-asind(sin_theta);
for i=1:1:size(C,1)
    for j=1:1:size(C,2)
        n=(size(C,2)+1)/2;
```

```
            C(1,n)=0;
    end
end
C
interpolated_I1=interpolation(C,gamma,I1)
E1=(interpolated_I1.*(cos_gamma.^3))/(h^2)
I2=xlsread('table of tube light2');
  I2;
[x,y]=meshgrid(0:1:20, 0:1:6);
points=[x(:),y(:)];
h=9.0000;
format short
d=((x-10).^2+(y-0).^2).^0.5;
l=((h^2+d.^2).^0.5);
cos_gamma=h./l;
gamma=acosd(cos_gamma);
sin_theta=((y-0)./d);
C=90-asind(sin_theta);
for i=1:1:size(C,1)
    for j=1:1:size(C,2)
n=(size(C,2)+1)/2;
             C(1,n)=0;
    end
end
C;
interpolated_I2=interpolation(C,gamma,I2);
E2=(interpolated_I2.*(cos_gamma.^3))/(h^2)
Ev=E3+E1+E2;
```

The vertical illuminance(E_v) at different grid points under targeted area are tabulated in Table 5.4.

Table 5.4 Simulated values of vertical illuminance (Ev) using MATLAB

11.56	15.79	20.74	26.35	32.18	37.62	41.07	41.28	39.34	39.22	39.84	39.22	39.34	41.28	41.07	37.62	32.18	26.35	20.74	15.79	11.56
11.38	15.43	20.17	25.45	31.00	36.17	39.39	39.78	38.18	37.91	38.51	37.91	38.18	39.78	39.39	36.17	31.00	25.45	20.17	15.43	11.38
10.87	14.62	19.07	23.86	29.02	33.84	36.55	36.57	34.93	34.72	35.18	34.72	34.93	36.57	36.55	33.84	29.02	23.86	19.07	14.62	10.87
10.09	13.47	17.44	21.76	26.03	29.86	32.22	32.54	31.21	30.43	30.67	30.43	31.21	32.54	32.22	29.86	26.03	21.76	17.44	13.47	10.09
9.12	12.10	15.48	19.07	22.64	25.83	27.93	27.65	26.24	25.94	25.81	25.94	26.24	27.65	27.93	25.83	22.64	19.07	15.48	12.10	9.12
8.10	10.55	13.38	16.37	19.35	21.98	22.95	22.69	21.46	21.64	21.14	21.64	21.46	22.69	22.95	21.98	19.35	16.37	13.38	10.55	8.10
7.11	9.11	11.42	13.85	16.26	17.75	18.50	18.30	17.81	17.62	16.89	17.62	17.81	18.30	18.50	17.75	16.26	13.85	11.42	9.11	7.11

5.2 DETERMINATION OF PHOTOPIC LUMINANCE (L_P)

The photopic luminance on each of the grid points are computed using the following steps :

Step 1: To obtain the photopic luminance reflectance table (R-table) for the specific kind of road is consulted.

Step 2: Road reflectance(ρ) values of all grid points are calculated using Matlab by interpolation program.

Step 3: The simulated values of photopic luminance(L_p) at each grid points are computed using Matlab through (5.2).

$$L_p = \rho E \tag{5.2}$$

The interpolated values of road reflectance are tabulated in Table 5.5.

Table 5.5 Interpolated values of road reflectance (ρ)

0.121	0.119	0.111	0.126	0.152	0.189	0.255	0.383	0.503	0.610	0.655	0.610	0.503	0.383	0.255	0.189	0.152	0.126	0.111	0.119	0.121
0.121	0.118	0.108	0.125	0.149	0.185	0.262	0.365	0.472	0.567	0.601	0.567	0.472	0.365	0.262	0.185	0.149	0.125	0.108	0.118	0.121
0.119	0.115	0.107	0.118	0.140	0.172	0.233	0.314	0.394	0.472	0.503	0.472	0.394	0.314	0.233	0.172	0.140	0.118	0.107	0.115	0.119
0.012	0.110	0.101	0.109	0.127	0.152	0.184	0.248	0.309	0.350	0.371	0.350	0.309	0.248	0.184	0.152	0.127	0.109	0.101	0.110	0.012
0.111	0.102	0.093	0.096	0.110	0.130	0.158	0.180	0.227	0.258	0.269	0.258	0.227	0.180	0.158	0.130	0.110	0.096	0.093	0.102	0.111
0.105	0.095	0.083	0.086	0.094	0.101	0.128	0.156	0.173	0.176	0.189	0.176	0.173	0.156	0.128	0.101	0.094	0.086	0.083	0.095	0.105
0.099	0.087	0.071	0.074	0.076	0.088	0.101	0.118	0.132	0.139	0.139	0.139	0.132	0.118	0.101	0.088	0.076	0.074	0.071	0.087	0.099

MATLAB CODE for Calculation of L_P:

```
X=(pi/180)*gamma;
```

```
A=tan(X)

P=xlsread('table of ro');

P;
```

Lp=E.*P; The simulated values of photopic luminance (L_p) for each grid points computed using MATLAB simulation is demonstrated in Table 5.6.

Table 5.6 Simulated values of photopic luminance (L_p)

0.021	0.033	0.048	0.094	0.175	0.317	0.617	1.336	2.560	3.685	3.960	3.685	2.560	1.336	0.617	0.317	0.175	0.094	0.048	0.033	0.021
0.021	0.034	0.049	0.096	0.177	0.313	0.614	1.221	2.253	3.181	3.288	3.181	2.253	1.221	0.614	0.313	0.177	0.096	0.049	0.034	0.021
0.020	0.031	0.045	0.080	0.145	0.241	0.435	0.777	1.342	1.546	2.010	1.546	1.342	0.777	0.435	0.241	0.145	0.080	0.045	0.031	0.020
0.002	0.024	0.035	0.060	0.099	0.154	0.233	0.392	0.627	0.842	0.971	0.842	0.627	0.392	0.233	0.154	0.099	0.060	0.035	0.024	0.002
0.013	0.018	0.024	0.037	0.058	0.087	0.130	0.174	0.266	0.378	0.422	0.378	0.266	0.174	0.130	0.087	0.058	0.037	0.024	0.018	0.013
0.009	0.012	0.015	0.023	0.033	0.044	0.066	0.088	0.120	0.147	0.166	0.147	0.120	0.088	0.066	0.044	0.033	0.023	0.015	0.012	0.009
0.006	0.007	0.009	0.013	0.018	0.024	0.032	0.041	0.053	0.060	0.062	0.060	0.053	0.041	0.032	0.024	0.018	0.013	0.009	0.007	0.006

5.3 DETERMINATION OF MESOPIC LUMINANCE (Lm)

The mesopic luminance on each of the grid points are computed using the following steps :

Step 1: To obtain the mesopic luminance, S/P ratio for the specific luminaire is consulted.
Step 2: Mesopic luminance values are interpolated using Matlab from the known photopic luminance values and S/P ratios using CIE191-2010 table as provided in Table 5.7.

Table 5.7 Values of L_m of the recommended Mesopic system as a function of photopic luminance and s/p ratio [CIE191]

	S/P	Photopic luminance / cd·m^{-2}						
		0,01	0,03	0,1	0,3	1	3	4,5
LPS ~	0,25	0,002 5	0,014 5	0,070 5	0,246 7	0,913 0	2,926 5	4,478 2
	0,35	0,003 5	0,017 4	0,075 0	0,254 5	0,925 3	2,936 7	4,481 2
	0,45	0,004 5	0,019 8	0,079 3	0,262 0	0,937 3	2,946 8	4,484 2
HPS ~	0,55	0,005 7	0,022 0	0,083 4	0,269 3	0,949 2	2,956 8	4,487 2
	0,65	0,006 9	0,023 9	0,087 3	0,276 4	0,960 8	2,966 6	4,490 1
	0,75	0,007 9	0,025 8	0,091 1	0,283 3	0,972 2	2,976 3	4,492 9
	0,85	0,008 8	0,027 5	0,094 7	0,290 1	0,983 5	2,985 9	4,495 8
	0,95	0,009 6	0,029 2	0,098 3	0,296 7	0,994 5	2,995 3	4,498 6
	1,05	0,010 4	0,030 8	0,101 7	0,303 2	1,005 4	3,004 6	4,501 4
MH warm white ~	1,15	0,011 1	0,032 3	0,105 1	0,309 6	1,016 1	3,013 9	4,504 1
	1,25	0,011 8	0,033 8	0,108 3	0,315 8	1,026 7	3,023 0	4,506 8
	1,35	0,012 5	0,035 3	0,111 5	0,322 0	1,037 1	3,031 9	4,509 5
	1,45	0,013 2	0,036 7	0,114 7	0,328 0	1,047 3	3,040 8	4,512 2
	1,55	0,013 8	0,038 1	0,117 8	0,333 9	1,057 5	3,049 6	4,514 8
	1,65	0,014 5	0,039 5	0,120 8	0,339 8	1,067 4	3,058 2	4,517 4
	1,75	0,015 1	0,040 8	0,123 8	0,345 5	1,077 3	3,066 8	4,520 0
	1,85	0,015 7	0,042 1	0,126 7	0,351 2	1,087 0	3,075 3	4,522 5
	1,95	0,016 3	0,043 4	0,129 5	0,356 8	1,096 6	3,083 6	4,525 0
	2,05	0,016 9	0,044 6	0,132 4	0,362 3	1,106 0	3,091 9	4,527 5
	2,15	0,017 4	0,045 9	0,135 2	0,367 7	1,115 4	3,100 1	4,529 9
	2,25	0,018 0	0,047 1	0,137 9	0,373 1	1,124 6	3,108 2	4,532 3
MH daylight ~	2,35	0,018 5	0,048 3	0,140 6	0,378 4	1,133 8	3,116 2	4,534 7
	2,45	0,019 1	0,049 5	0,143 3	0,383 6	1,142 8	3,124 1	4,537 1
	2,55	0,019 6	0,050 6	0,145 9	0,388 8	1,151 7	3,131 9	4,539 5
	2,65	0,020 1	0,051 8	0,148 5	0,393 9	1,160 5	3,139 6	4,541 8
	2,75	0,020 7	0,052 9	0,151 1	0,398 9	1,169 3	3,147 3	4,544 1

The calculated values of mesopic luminance (L_m) for each grid points calculated is demonstrated in Table 5.8.

Table 5.8 Calculated values of mesopic luminance (L_m)

0.013	0.023	0.036	0.075	0.149	0.28	0.571	1.281	2.517	3.652	3.937	3.652	2.517	1.281	0.571	0.28	0.149	0.075	0.036	0.023	0.013
0.014	0.024	0.037	0.077	0.151	0.276	0.568	1.164	2.207	3.146	3.247	3.146	2.207	1.164	0.568	0.276	0.151	0.077	0.037	0.024	0.014
0.013	0.021	0.034	0.063	0.122	0.21	0.394	0.725	1.286	1.493	1.917	1.493	1.286	0.725	0.394	0.21	0.122	0.063	0.034	0.021	0.013
0.002	0.016	0.025	0.046	0.08	0.13	0.203	0.353	0.58	0.788	0.912	0.788	0.58	0.353	0.203	0.13	0.08	0.046	0.025	0.016	0.002
0.007	0.011	0.016	0.027	0.045	0.069	0.108	0.148	0.233	0.34	0.382	0.34	0.233	0.148	0.108	0.069	0.045	0.027	0.016	0.011	0.007
0.004	0.006	0.009	0.015	0.023	0.032	0.052	0.071	0.099	0.124	0.141	0.124	0.099	0.071	0.052	0.032	0.023	0.015	0.009	0.006	0.004
0.002	0.002	0.004	0.007	0.011	0.016	0.022	0.03	0.048	0.047	0.048	0.047	0.048	0.03	0.022	0.016	0.011	0.007	0.004	0.002	0.002

5.4 DETERMINATION OF ADAPTATION LUMINANCE (L_a)

The adaptation luminance on each of the grid points are computed using the following steps :

Step 1: The visual angles between the source and grid points) in degrees are computed in MATLAB.

Step 2: Vertical illuminance values on all grid points for surrounding light sources are calculated in MATLAB.

Step 3: Veiling luminance is calculated using (5.3) given using MATLAB.

$$L_{veiling} = \frac{260}{\theta^3} Ev \qquad (5.3)$$

Step 4: Local luminance (L_{local}) values are the photopic luminance values on the grid points for all individual sources are calculated using MATLAB .

Step 5: The adaptation luminance(L_a) is the sum of the values of local luminance and Veiling luminance at each of the grid points. Therefore,

$$L_a = L_{veiling} + L_{local} \qquad (5.4)$$

MATLAB CODE for Calculation of L_a:

```
x=[0:5:100];

y=[0:5:30];

[xx,yy]=meshgrid(x,y);

a=(1.4^2+(yy+6).^2).^0.5

b=(((xx+1.7).^2)+((3.9-yy).^2)+(2.15^2)).^0.5

c=((0.75^2)+9.9^2+1.7^2)^0.5

d=((a.^2)-(b.^2)+(c^2))./(2*c)

e=d./a

theta=acosd(e);

h=theta.^(-3)
```

i=260*h

```
size(i)

size(Ev)

L= i.*Ev

La=Lp+L

m=theta.^(2)

n=(1.5).*theta

p=m+n;

o=Ev./p;

Lv=(9.2).*o

La=Lp+Lv;
```

The simulated values of mesopic luminance (L_a) for each grid points computed using MATLAB simulation is demonstrated in Table 5.9.

Table 5.9 Simulated values of adaptation luminance (L_a)

0.062	0.098	0.143	0.281	0.525	0.950	1.850	4.010	7.700	11.147	11.970	11.147	7.700	4.010	1.850	0.950	0.525	0.281	0.143	0.098	0.062
0.064	0.103	0.147	0.287	0.531	0.938	1.840	3.660	6.780	9.590	9.916	9.590	6.780	3.660	1.840	0.938	0.531	0.287	0.147	0.102	0.064
0.061	0.091	0.136	0.239	0.435	0.722	1.300	2.330	4.030	4.650	6.046	4.650	4.030	2.330	1.300	0.722	0.435	0.239	0.136	0.091	0.061
0.005	0.073	0.105	0.179	0.296	0.463	0.701	1.170	1.884	2.530	2.917	2.530	1.884	1.170	0.701	0.463	0.296	0.179	0.105	0.073	0.005
0.040	0.054	0.072	0.112	0.174	0.261	0.391	0.522	0.799	1.130	1.260	1.130	0.799	0.522	0.391	0.261	0.174	0.112	0.072	0.054	0.039
0.028	0.035	0.045	0.068	0.098	0.130	0.198	0.265	0.361	0.440	0.499	0.440	0.361	0.265	0.198	0.130	0.098	0.068	0.045	0.035	0.027
0.019	0.021	0.026	0.040	0.055	0.073	0.095	0.124	0.158	0.181	0.185	0.181	0.158	0.124	0.095	0.073	0.055	0.040	0.026	0.020	0.018

CHAPTER 6:

RESULT ANALYSIS

6.0 INTRODUCTION

As the lighting level of many outdoor areas (especially Road) fall under mesopic region, it is necessary to evaluate lighting parameters in mesopic photometry system only. However due to unavailability of mesopic meters, now-a-days photopic quantities are measured first and then corresponding mesopic parameters are calculated. Again in outdoor lighting application areas it is also required to consider adaptation luminance due to wide field of view. Therefore to get an idea about light distribution in the area of measurement, point specific luminance in photopic, mesopic and adaptation conditions are evaluated by MATLAB PROGRAM.

In this thesis work photopic luminance were evaluated at first from the luminous intensity distribution table (I –table) of a luminaire. Then the mesopic luminance values are calculated from CIE 191:2010 Table (Table:4.1) using the S/P ratio of the lamp. Adaptation luminance for the said area of measurement is calculated by the method described in Chapter 4 .The resultsare compared in different forms as discussed below:

1. MATLAB simulation result of Photopic, mesopic & Adaptation Luminance.

2. Comparison of Average Photopic, mesopic & Adaptation Luminance.

3. Comparison of Luminance Distribution.

6.1 MATLAB SIMULATED RESULT OF PHOTOPIC ,MESOPIC AND ADAPTATION LUMINANCE IN cd/m^2

The MATLAB simulated results are consolidated in Table 6.1, Table 6.2, and Table 6.3 for photopic , mesopic and adaptation luminance respectively.

Table 6.1 MATLAB simulation result of photopic luminance (Lp)

0.021	0.033	0.048	0.094	0.175	0.317	0.617	1.336	2.560	3.685	3.960	3.685	2.560	1.336	0.617	0.317	0.175	0.094	0.048	0.033	0.021
0.021	0.034	0.049	0.096	0.177	0.313	0.614	1.221	2.253	3.181	3.288	3.181	2.253	1.221	0.614	0.313	0.177	0.096	0.049	0.034	0.021
0.020	0.031	0.045	0.080	0.145	0.241	0.435	0.777	1.342	1.546	2.010	1.546	1.342	0.777	0.435	0.241	0.145	0.080	0.045	0.031	0.020
0.002	0.024	0.035	0.060	0.099	0.154	0.233	0.392	0.627	0.842	0.971	0.842	0.627	0.392	0.233	0.154	0.099	0.060	0.035	0.024	0.002
0.013	0.018	0.024	0.037	0.058	0.087	0.130	0.174	0.266	0.378	0.422	0.378	0.266	0.174	0.130	0.087	0.058	0.037	0.024	0.018	0.013
0.009	0.012	0.015	0.023	0.033	0.044	0.066	0.088	0.120	0.147	0.166	0.147	0.120	0.088	0.066	0.044	0.033	0.023	0.015	0.012	0.009
0.006	0.007	0.009	0.013	0.018	0.024	0.032	0.041	0.053	0.060	0.062	0.060	0.053	0.041	0.032	0.024	0.018	0.013	0.009	0.007	0.006

Table 6.2 Calculated result of mesopic luminance (Lm)

0.013	0.023	0.036	0.075	0.149	0.28	0.571	1.281	2.517	3.652	3.937	3.652	2.517	1.281	0.571	0.28	0.149	0.075	0.036	0.023	0.013
0.014	0.024	0.037	0.077	0.151	0.276	0.568	1.164	2.207	3.146	3.247	3.146	2.207	1.164	0.568	0.276	0.151	0.077	0.037	0.024	0.014
0.013	0.021	0.034	0.063	0.122	0.21	0.394	0.725	1.286	1.493	1.917	1.493	1.286	0.725	0.394	0.21	0.122	0.063	0.034	0.021	0.013
0.002	0.016	0.025	0.046	0.08	0.13	0.203	0.353	0.58	0.788	0.912	0.788	0.58	0.353	0.203	0.13	0.08	0.046	0.025	0.016	0.002
0.007	0.011	0.016	0.027	0.045	0.069	0.108	0.148	0.233	0.34	0.382	0.34	0.233	0.148	0.108	0.069	0.045	0.027	0.016	0.011	0.007
0.004	0.006	0.009	0.015	0.023	0.032	0.052	0.071	0.099	0.124	0.141	0.124	0.099	0.071	0.052	0.032	0.023	0.015	0.009	0.006	0.004
0.002	0.002	0.004	0.007	0.011	0.016	0.022	0.03	0.048	0.047	0.048	0.047	0.048	0.03	0.022	0.016	0.011	0.007	0.004	0.002	0.002

Table 6.3 MATLAB simulation result of adaptation luminance (La)

0.062	0.098	0.143	0.281	0.525	0.950	1.850	4.010	7.700	11.147	11.970	11.147	7.700	4.010	1.850	0.950	0.525	0.281	0.143	0.098	0.062
0.064	0.103	0.147	0.287	0.531	0.938	1.840	3.660	6.780	9.590	9.916	9.590	6.780	3.660	1.840	0.938	0.531	0.287	0.147	0.102	0.064
0.061	0.091	0.136	0.239	0.435	0.722	1.300	2.330	4.030	4.650	6.046	4.650	4.030	2.330	1.300	0.722	0.435	0.239	0.136	0.091	0.061
0.005	0.073	0.105	0.179	0.296	0.463	0.701	1.170	1.884	2.530	2.917	2.530	1.884	1.170	0.701	0.463	0.296	0.179	0.105	0.073	0.005
0.040	0.054	0.072	0.112	0.174	0.261	0.391	0.522	0.799	1.130	1.260	1.130	0.799	0.522	0.391	0.261	0.174	0.112	0.072	0.054	0.039
0.028	0.035	0.045	0.068	0.098	0.130	0.198	0.265	0.361	0.440	0.499	0.440	0.361	0.265	0.198	0.130	0.098	0.068	0.045	0.035	0.027
0.019	0.021	0.026	0.040	0.055	0.073	0.095	0.124	0.158	0.181	0.185	0.181	0.158	0.124	0.095	0.073	0.055	0.040	0.026	0.020	0.018

6.2 COMPARISON OF AVERAGE LUMINANCE (LAVERAGE)

Point specific photopic luminance of all the (7x21) grid points of the field has been calculated from the luminous intensity distribution (I-table) of a luminaire by using MATLAB PROGRAM. This Photopic luminance and corresponding S/P ratio of main lamp determine the mesopic luminance (Lm). Corresponding adaptation luminance (La) (considering the effects of surrounding lighting ambience) has been determined .This procedure is carried out for a single main lamp and three different surrounding lighting environments of cool and white lighting. The Average value of the point specific luminance of all the grid points are considered and a comparison graph has been drawn.

Table 6.4 Average luminance (in cd/m2)

PHOTOPIC LUMINANCE (Lp)	MESOPIC LUMINANCE (Lm)	ADAPTATION LUMINANCE(La)
0.4274	0.404935	1.286

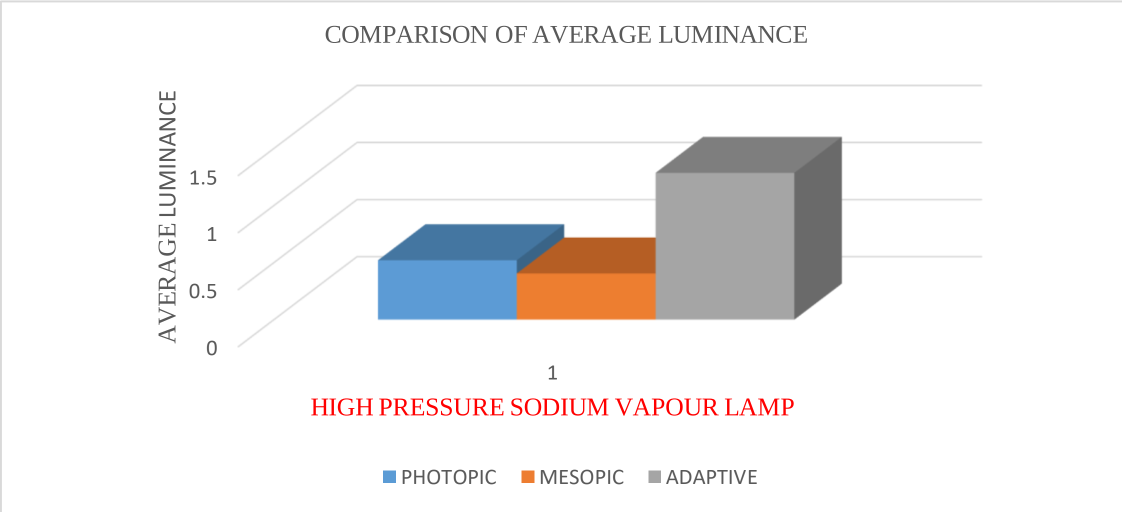

Fig:6.1 Comparison of Average Luminance for HPSV

The value of Average Photopic luminance (Lp) is 0.4274 in cd/m2 .Average Mesopic luminance (Lm) is 0.404935 .The value is lower than Average photopic luminance (Lp) because the S/P ratio of the light source (HPSV) is lower than one.

The veiling luminance $L_{veiling}$ was added to the average photopic luminance Lp of the fields and this sum was considered to be the adaptation luminance (La).

The value of the adaptation luminance is higher than that of the photopic and mesopic luminance due to use of surrounding light sources

6.3 COMPARISON OF LUMINANCE DISTRIBUTION

Surface plots of Photopic luminance, Mesopic luminance and Adaptation luminance and their comparisons are shown here.

6.3.1 Photopic Luminance Distribution

Photopic luminance were evaluated at first from the luminous intensity distribution (I-table) of a luminaire by using MATLAB PROGRAM. Then the average values of simulated photopic luminance (Lp) calculated. Photopic luminance (Lp), are shown in table8.1. The Luminance distribution of Photopic luminance (Lp) shown below:

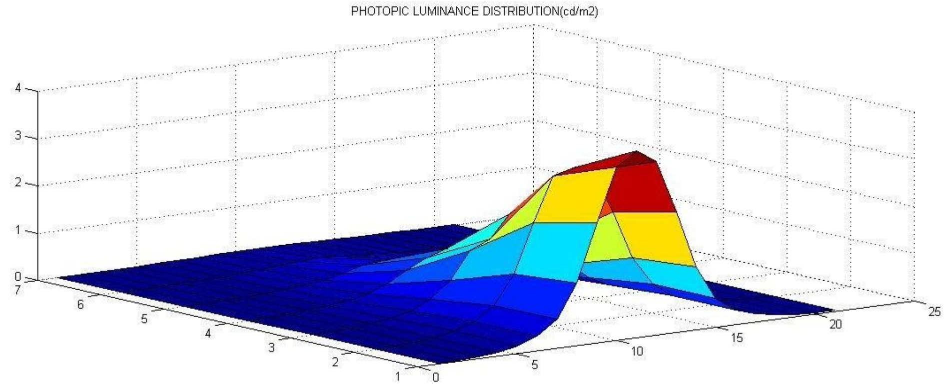

Fig:6.2 Photopic Luminance Distribution

6.3.2 Mesopic Luminance Distribution

After evaluating photopic luminance for the entire field of measurement corresponding mesopic luminance values are calculated from CIE 191:2010 Table (Table:4.1) using the S/P ratio of the lamp. Average values of mesopic luminance values are calculated. The Luminance distribution of Mesopic luminance (Lm) is shown below:

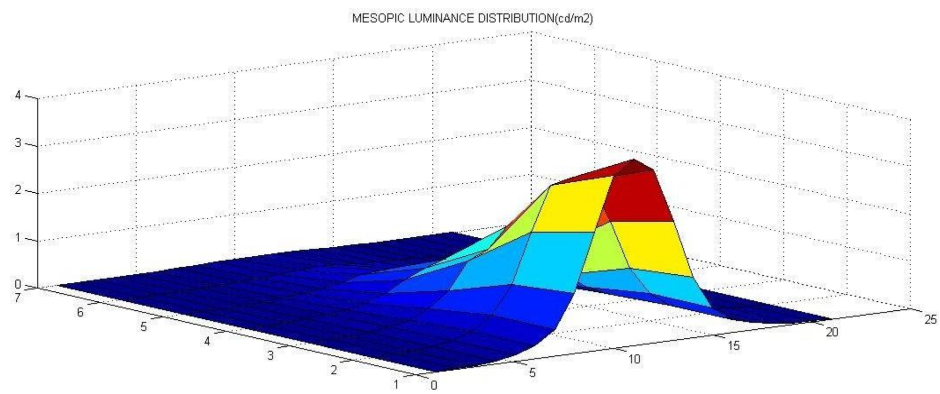

Fig:6.3 Mesopic Luminance Distribution

6.3.3 Adaptation Luminance Distribution

The veiling luminance Lveiling was added to the average photopic luminance Lp of the fields and this sum was considered to be the adaptation luminance (La).

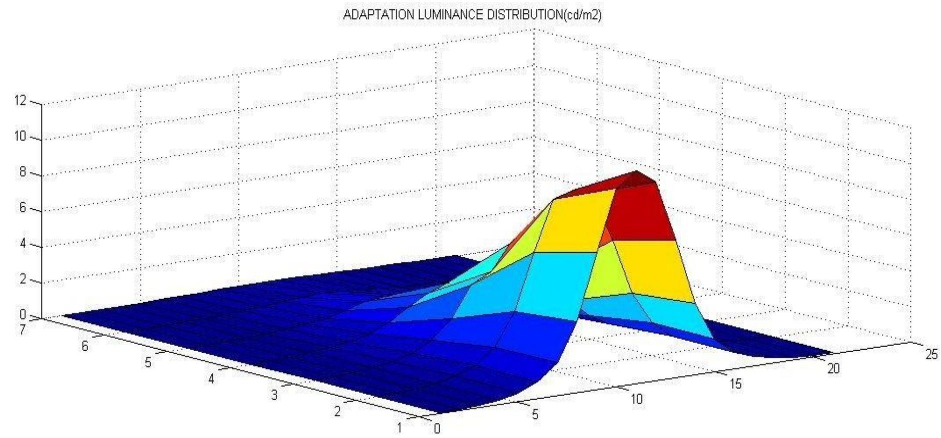

Fig: 6.4 Adaptation Luminance Distribution

The veiling luminance Lveiling was added to the average photopic luminance (Lp), and this sum was considered to be adaptation states. The results shows that the increment in adaptation state when the main light source was High pressure sodium vapour lamp and surrounding light source was cool FTL.

6.4 COMPARISON OF POINT SPECIFIC PHOTOPIC AND MESOPIC LUMINANCE

The luminance distributions thus obtained for HPSV light source were sorted in incremental order and then Photopic vs Mesopic and Photopic vs Adaptation luminance graphs are plotted.

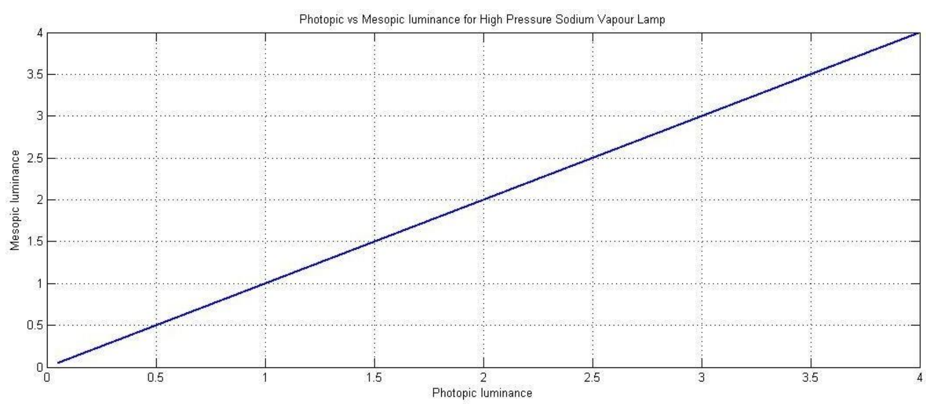

Fig:6.5 Photopic VS Mesopic Luminance graph

From this plot it can be known said that as the Photopic luminance values increase, Mesopic luminance values also increase for HPSV lamps.

6.5 DISCUSSION

From the results obtained , the following points can be summarised.

- Here, it is observed that Mesopic luminance is less as compared to photopic luminance when S/P ratio is less than 1

- Mesopic luminance and adaptation luminance are not same for the entire area of measurement (AOM) in the presence of surrounding light sources. The surrounding light source have a significant role on adaptation luminance.
  Therefore, in any field where veiling sources are present in line of sight, it is better to consider adaptation luminance over the mesopic luminance.

- The nature of surrounding light source plays an important role on effective adaptation luminance to observer's eyes.
  Therefore it is more accurate to consider adaptation luminance instead of photopic & mesopic luminance in case of outdoor lighting under mesopic region.

CHAPTER 7:

CONCLUSION AND FUTURE SCOPE

7. 0 CONCLUSIONS & FUTURE SCOPE

Lamps having lower S/P ratio, such as HPSV, have lower Lmes value than Lp values in the mesopic zone. Thus, human eye would perceive less brightness in this environment. To achieve same brightness, higher wattage lamps would be required, leading to high energy consumption. Thus for efficient energy management, using these lamps in mesopic zones would not be recommended. HPSVs are mainly used due to their robust construction, good luminous efficacy and good lifespan. But in the mesopic zone they seem to perform poor. Lamps of higher S/P ratio, such as CWLED can be used. It has higher mesopic value than photopic value due to its high s/p ratio. Those lamps would deliver most energy efficient performance in mesopic region.

When surrounding light sources are cool white FTL, Adaptation luminance values are higher than Photopic luminance values for HPSV. After comparing Lm and La values it can be seen that when surrounding light sources are cool white FTL, average Lm value is lesser than average La value for HPSV lamp.

From the comparison of Point Specific Lp, Lm & La values we can say that, As the Photopic luminance values increase, Mesopic luminance values also increase. But there is no such relation between the Photopic luminance and Adaptation luminance.

Our actual objective is to find out mesopic and adaptation luminance in outdoor condition. So in future the experiment can be done in actual outdoor conditions. The effects of dust, rain and ambient temperature variations, which significantly affect lamp performance as well as human visual performance, can be taken into considerations. Also a significant weather condition is fog. HPSV is proven to provide better recognition performance under fog. Performance of LEDs under foggy weather is also a future scope of judgment. The results are simulated depending upon the I- Table value of a particular light. By using this procedure we can find out the mesopic and adaptation luminance of any type of light for outdoor and easily can compare for better option.

In this thesis work High pressure Sodium Vapor Lamp were used as main light source so in future this study can also be performed for more than one light source Metal Halide, Cool white LED, Warm White LED and their performance & adaptation luminance in mesopic photometry system can also be studied.

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