

Studies on Visual Adaptation Characteristics for Application of Mesopic Photometry

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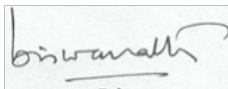
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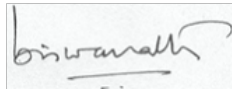
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Sangita Sahana

Date

Dedicated in loving memory of my father

Late Dhruba Pada Sahana

Abstract

The sensitivity of the human eye varies with the variation in illumination conditions throughout the visible range. The response for photopic vision is characterized by photopic spectral luminous efficiency function and dominated by cone cells. Conversely, the rods dominate the scotopic spectral luminous efficiency function, which is considered for scotopic vision. For the intermediate zone, both types of photoreceptors participate in vision and are defined as mesopic vision. There is no fixed response characteristics for mesopic vision; rather, the response shifts from the scotopic to the photopic zone with an increase in luminance, and vice versa with a fall in luminance. Mesopic photometry is applied to a variety of outdoor and roadway lighting applications. Considering the mesopic vision in outdoor and lighting design along with the photopic vision can help create a balance between visibility and energy efficiency, ensuring optimal performance in varying light conditions. By incorporating mesopic photometry in outdoor lighting design, designers can better understand how the human eye perceives light in real-world scenarios, leading to more effective and sustainable lighting solutions based on adaptation luminance.

In this work experimental analysis of different lamp performances in mesopic zone for area lighting installations has been performed in both simulation and laboratory environments. The photopic luminance due to a light source is computed from its luminous intensity distribution table. Corresponding mesopic and adaptation luminance values are also computed in the presence of two different surrounding lighting conditions with different spectral compositions. All those parameters are measured again in a laboratory environment for the same lamp combinations.

From both the computed and measured data, it has been found that

the lamps with more blue content in their spectrum i.e. the lamps with higher scotopic/photopic (S/P) ratio provide higher mesopic and adaptation luminance as compared to the corresponding photopic luminance.

The mesopic adaptation luminance is estimated in the presence of two different surrounding lighting conditions obtained by two types of light sources of different spectral compositions i.e. yellow-enriched warm white and blue-enriched cool white. Detailed study of experimental results shows that spectral characteristics of surrounding light sources and the location of these luminaires have notable effects on mesopic and adaptation luminance. The blue-enriched cool white LED (CWLED) lamp shows most effective adaptation state of the observer in presence of cool white surrounding ambiance. Therefore, these lamps show better photometric performance and would deliver more energy-efficient performance in the mesopic zone as compared to conventional lamps i.e. high pressure sodium vapour lamp.

The unit power density (UPD) values are calculated for all four types of lamps on a sample area. The number of lamps required for a lighting design is reduced since these cool white lamps are more effective in mesopic vision, which results in lower power and energy consumption for any given application area and it ultimately leads to cost-saving and energy-efficient lighting solutions. Additionally, the reduced power consumption also contributes to a lower carbon footprint and helps to promote sustainability.

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List of Abbreviations

AOM	Area of Measurement
CIE	Commission Internationale De l'Eclairage
CW	Cool White
CELED	Cool White LED
CWSLE	Cool White SLE
CWSLS	Cool White SLS
EM	Eye Movements
FTL	Fluorescent Tube Lamp
HPSV	High-Pressure Sodium Vapour
IESNA	Illuminating Engineering Society of North America
LD	Luminance Distributions
LED	Light Emitting Diode
MES1	Mesopic 1
MES2	Mesopic 2
MH	Metal Halide
MLS	Main Light Source
MOVE	Mesopic Optimisation of Visual Efficiency
S/P	Scotopic/Photopic
SLE	Surrounding Luminance Effect
SLS	Surrounding Light Sources
SPD	Spectral Power Distribution
USP	Unified System Of Photometry
WLED	White LED
WW	Warm White
WWSLE	Warm White SLE
WWSLS	Warm White SLS

List of Acronyms

$V(\lambda)$	Photopic Spectral Luminous Efficiency Function
$V'(\lambda)$	Scotopic Spectral Luminous Efficiency Function
$V_{mes}(\lambda)$	Mesopic Luminous Efficiency Function
K'_m	Maximum Luminous Efficacy For Scotopic Vision
K_m	Maximum Luminous Efficacy For Photopic Vision
$S_\lambda(\lambda)$	Spectral Distribution of Light Source
λ	Wavelength
X	Adaptation Coefficient in USP System
L_p	Photopic Luminance
L_s	Scotopic Luminance
m	Adaptation Coefficient in MOVE System
$M(x)$	A Normalizing Function
x	Adaptation Coefficient in MOVE System
L_{mes}	Mesopic Luminance
m_1	Adaptation Coefficient in MES1 System
$M(m_1)$	A Normalizing Function in MES1 System
n	Iteration Step
$M(m_2)$	A Normalizing Function in MES2 System
m_2	Adaptation Coefficient in MES2 System
$M(m)$	A Normalizing Function in CIE191 System
m	Adaptation Coefficient in CIE191 System
$L_e(\lambda)$	Spectral Radiance
L_{veil}	Veiling Luminance
θ_d	Visual Angle Between The Source And A Task Point
E_n	Illuminance At The Observer's Eye
E_v	Vertical Illuminance Due to SLE Source
$d\omega$	Solid Angle of The Image
$f_{SLE}(\theta, \phi)$	A Function In The Retinal Coordinate System
$\sigma_{\theta'}$	Standard Deviations For The Horizontal Directions
$\sigma_{\phi'}$	Standard Deviations For The Vertical Directions
$L(\theta, \phi)$	LD Projected To The Retinal Coordinate System
$L(\theta', \phi')$	Luminance Distribution
$L_{effective}(\theta, \phi)$	Effective Luminance Distribution
$L_a(\theta, \phi)$	Adaptation Luminance Distribution
$P_{AOM}(\theta, \phi)$	Probability of Any Test Point inside AOM
L_{AOM}	Adaptation Luminance of Aom
$E_{v,vertical}$	Vertical Illuminance At The Observer's Eye Due to SLS
A	Observer's Age in Years
p	Eye Pigment Factor
R_{SP}	S/P Ratio
F_{mes}	Mesopic Enhancement Factor
L_a	Adaptation Luminance
E_p	Point Specific Illuminance
$I_p(C, \gamma)$	Luminous Intensity Distribution
h	Luminaire Mounting Height
$q(\beta, \gamma)$	Luminaire Coefficient of The Surface
$r(\beta, \gamma)$	Reduced Luminance Coefficient
L_{local}	Local Luminance

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1 General Introduction

1.1 Overview

The mesopic photometry region includes road lighting and many outdoor area lighting applications. The Commission Internationale de l'Eclairage (International Commission on Illumination) (CIE) published a technical report for visual performance-based mesopic photometry in 2010 based on peripheral task [3]. The luminance level for road lighting and many outdoor application areas falls under the mesopic region, the design and assessment should be performed considering the mesopic photometry system. Mesopic photometry system is expected to provide more visually effective and energy-efficient lighting system designs for outdoor lighting applications. In this system, the adaptation luminance of the area under measurement has a significant influence on an observer's vision. As the high adaptation luminance generally produces a high threshold contrast, the estimated visual range reduces effectively [4–6]. So the effect of the adaptation luminance is different from the effect of background luminance. The adaptation field is generally decided by considering the peripheral state of the observer[6–8]. The mesopic photometric quantity computation depends on the observer's visual field, and the required amount of adaptation luminance varies depending on the scene in the observer's visual field [9].

1.2 Background

The International Commission on Illumination has provided a mesopic photometry system which is based on the peripheral visual performance of tasks and it provides a database to find the value of mesopic

luminance corresponding to the photopic luminance (within the range of 0.005–5 cd/m²) and the relevant scotopic/photopic ratio (i.e., S/P ratio) of lamps [3–12]. At present, recommendations for outdoor lighting are primarily based on photopic photometry, even if luminance values are within the mesopic range. It is established that only photopic vision is responsible for on-axis object recognition. But if the effects of the peripheral vision are included in case of road lighting, then the CIE mesopic system may be considered [5]. This mesopic photometry system is valid for vast majority of outdoor lighting applications under mesopic conditions [13–16]. For the implementation of the mesopic photometry system in those real lighting applications, the relevant application field and the adaptation luminance of the area under evaluation must be determined based on the mesopic luminous efficiency function considering the adaptation state of the observers to predict the task performances in the scene appropriately [2] which has a significant influence on an observer’s vision. But still, the proper definition of the visual adaptation field has not been defined as the calculation is complex due to variation in their area, position, and size [17, 18].

Several researches are going on to evaluate the significance of replacing high pressure sodium vapor lamps by white light sources like white LED (WLED) lamps [7] in outdoor lighting considering mesopic effects. For a given photopic luminance, light sources with a higher concentration of major short-wavelength (400–500 nm) content in their SPD will appear brighter. So, lighting design based on photopic system will lead to wastage of electric energy and there will be significant amount of radiant energy reflecting from the pavement and escaping into the night sky [16, 19–25]. Therefore, the lighting designers should be able to create outdoor lighting applications with more effec-

tiveness and lower energy consumption considering the mesopic photometry system, as opposed to photopic aspect. However, the dependency of adaptation luminance on spectral composition of surrounding light sources (SLSs) needs serious attention in case of outdoor lighting within a city, viz., street lighting, car parking areas, parks, and pedestrian areas etc.

1.3 Literature Survey

As the sensitivity of human eye is not same for the entire visible range of wavelength, not any single spectral luminous efficiency function can define different types of vision perceived by human eye. Under high light levels i.e. under photopic vision when luminance level is more than 5 cd/m^2 , cone cells are responsible for human vision. Under very low light levels i.e. for scotopic vision when luminance level is less than 0.005 cd/m^2 , rod cells control the human vision [3–7, 12, 26]. However, in between these two light levels, when both the cone and rod cells remain active, this vision is termed as mesopic vision. Before the issuance of CIE 191:2010, the researchers proposed one unified system of photometry (USP) system for mesopic vision which depends on the reaction time of the observer [16]. But this system was mainly concentrated on achromatic tasks. Another system for mesopic vision, MOVE (Mesopic Optimisation of Visual Efficiency) was based on visual performance for the range of $0.01\text{--}10 \text{ cd/m}^2$ of photopic luminance [10]. The intermediate systems of these USP and MOVE, two other systems, MES1 and MES2 were developed for mesopic region [3]. All these methods together provide interaction between visual performance for a wide range of visual conditions.

In 2010, the CIE has recommended a mesopic photometry system that provides the mesopic table to obtain values of the mesopic luminance corresponding to some selected photopic luminance (within the

range of 0.005 cd/m^2 to 5 cd/m^2) for all relevant S/P ratio (i.e. Scotopic/Photopic ratio) of lamps [3]. The mesopic photometry system also defines mesopic luminous efficiency function $V_{mes}(\lambda)$ as a linear combination of photopic luminous efficiency function $V(\lambda)$ and scotopic luminous efficiency function $V'(\lambda)$, whose effectiveness is dependent upon the luminance to which the eyes are adapted, also known as the adaptation luminance. Adaptation field refers to the field of view that contributes to the adaptation luminance. In CIE 191:2010, $V_{mes}(\lambda)$ is defined by some equations as discussed in Chapter 2 in detail.

A new corrected photopic luminance table has been developed [15] for road lighting design by lighting designers in mesopic applications. The authors have also shown that, even though on-axis object recognition solely depends on photopic vision, there are still many reasons to use the CIE mesopic system.

This mesopic photometry system is valid for a vast majority of outdoor lighting applications under mesopic conditions [11, 27]. Therefore, for implementation of the mesopic photometry system the relevant visual field and the adaptation luminance subjected to the adaptation field can be evaluated to determine the mesopic luminous efficiency function [7]. The peripheral adaptation state of the observers' eyes should be used to determine the adaptation luminance, as the CIE 191, 2010 was developed based on peripheral task performance [6–8, 28]. Adaptation field can be defined using luminance distributions (LDs) and observers' line of sight [2, 18, 29–32]. The mesopic adaptation model, designed in laboratory environment [10, 16], but the laboratory environments are subjected to uniform LDs, whereas outdoor lit scenes typically have complex luminance distributions which can affect the visual performance [6]. Four factors i.e. luminance distribution (LD), observers' eye movements (EM), surrounding luminance effect (SLE),

and area of measurement (AOM) were considered for the computation of adaptation luminance in a model [2]. They have considered each factor as a two-dimensional geometrical function. Using four calculation steps, the approach determines the adaptation luminance for the measurement area. The results of the simulation of adaptation luminance were compared and the method was applied to luminance distributions of different outdoor areas. Based on the comparison of the results, it has been found that the average luminance is generally a reliable approximation of adaptation luminance of the measurement area. However, there are some exceptions in few areas with the presence of many sources with high luminance within the surrounding area of measurement. The use of the local luminance (the luminance of the test object) as the adaptation luminance is recommended in IESNA TM-12-12 [21] without the pedestrian area which has many sources with high brightness in the surrounding area of AOM.

This same condition applies to outdoor lighting & researchers have considered two simplified methods to measure the mesopic luminance [14], namely the adaptation spectral power distribution method and source SPD method. The source SPD approach is less sensitive for lighting scenes with a variety of light sources, according to error simulations. Measurements of the surrounding luminance effect with respect to the angle between a peripheral task point and a point source have been made through several mesopic vision tests [11–16]. The findings demonstrate that, in contrast to current models, the surrounding luminance effect at a peripheral task point diminishes with increasing angle at a greater slope.

Although street and outdoor lighting installations incorporate different types of light sources such as high-pressure sodium vapour (HPS), metal halide (MH), white Light Emitting Diode (WLED) lamps, it has been observed that WLEDs are more effective and energy efficient

in mesopic lighting conditions [25, 31–36]. Several researchers are going on to evaluate the significance of replacing high pressure sodium vapour lamps by white light sources like metal halide, white LED (WLED) lamps [9] in outdoor lighting considering mesopic effects. As light sources with higher amount of short-wavelength content in its SPD, emitted radiation will be seen as brighter for the same photopic luminance. So, lighting design based on photopic system will lead to wastage of electric energy and also there will be significant amount of radiant energy reflecting from the pavement and escaping into the night sky [19]. A study revealed that, in terms of both safety and energy efficiency, lighting a concrete pathway with LEDs was the better option to select [24, 37] due to its higher S/P ratio. Additionally, it has been noted that the light source selection criteria and the necessary regulatory values can be modified to better suit the visual processes of the human eye when artificial street lighting is present. A variety of energy requirements for lighting installation are also provided by them. This makes accurate electrical designs or predictions possible and removes the need to specify the precise lighting configuration. The results show that, under artificial street lighting conditions, the light source selection criteria and the required regulatory values can be adjusted to the human eye’s vision process. They also provide a statistical range of energy requirements for lighting installation. This eliminates the need to specify the exact lighting setup and enables the creation of accurate electrical designs or predictions.

It has also been observed that under artificial street lighting conditions, the light source selection criteria and the required regulatory values can be adjusted to the human eye’s vision process. They also provide a range of energy requirements for lighting installation. This eliminates the need to specify the exact lighting setup and enables the accurate electrical designs or predictions. Along with providing a

statistical range of energy requirements for lighting installation, the results also demonstrate that the light source selection criteria and the necessary regulatory values can be adjusted to the human eye's vision process under normalized artificial street lighting conditions. This allows for the generation of precise electrical designs or estimations without the need to specify the precise lighting configuration [25].

A provisional model was introduced to predict scene brightness for different outdoor lighting applications, and each illuminated to different levels by light sources with different S/P ratios [19, 20, 33]. The WLEDs shows higher adaptation luminance in presence of any cool white surrounding sources [34]. The researchers have compared the average luminance and adaptation field luminance for different mesopic applications based on the simulation and field measurements of the adaptation field areas. However, dependency of mesopic luminance on spectral composition of surrounding light sources (SLs) needs to be studied in case of outdoor lighting within a city, viz., street lighting, car parking areas, parks, and pedestrian areas. The result also shows that lighting associated with the best subjective ratings also had the lowest power density due to its better performance under mesopic condition with higher S/P ratio. Due to the energy saving potential of light emitting diodes (LEDs), these lamps are considered as the best alternative to conventional lamps in outdoor lighting applications nowadays. Under mesopic conditions, white light sources such as metal halide (MH), LEDs provide better perception than yellow light sources [8, 22]. The researchers found that the retrofitted application with LEDs can reduce energy use and so a sustainable option to replace the conventional lighting systems [14, 23, 32].

For outdoor lighting applications, adaptation luminance has a marked influence on observer's estimation and therefore, determining the adaptation luminance is necessary to obtain the mesopic luminous efficiency

function, which can accurately predict task performances in the scene [31]. The peripheral adaptation state of the observers' eyes is used to calculate the adaptation luminance and it depends on veiling luminance and the local photopic luminance [9, 15]. Using the average luminance of the AOM as the adaptation luminance when there are numerous high-luminance sources nearby the illuminated area may require additional checking, according to the research. On the other hand as mesopic luminance meters are not available, S/P ratio of light source is required for the calculation of mesopic luminance. It has been found that the lamps with higher S/P ratio, provide higher luminous efficacy during mesopic vision. The lamps which have more blue content in their spectrum, have higher S/P ratio and hence relatively high output in short wavelength region [10].

Therefore, for outdoor lighting designs, the lighting designers should be able to provide more visually effective and energy efficient solutions compared to photopic aspect considering the mesopic dimensioning. The above literature survey reveals that the researchers have compared the average luminance and adaptation field for different outdoor lighting applications based on the simulation and field measurements of the adaptation field areas. Now the question is whether the above findings are application specific or universal. To address this question, it is necessary to apply the methods for other outdoor lighting applications and to define the adaptation characteristics accordingly.

1.4 Problem Statement

In this research work, the adaptation characteristics are to be studied to define the visual adaptation field, adaptation and viewing conditions on the basis of peripheral adaptation state of observers for the implementation of mesopic photometry system in outdoor lighting. A model is also to be developed to predict the performance evaluation of

different light sources in outdoor lighting under mesopic dimensioning.

1.5 Objectives

I. To evaluate the visual adaptation field in outdoor light installation for implementation of mesopic photometry in the areas where this system can be used.

II. To investigate the performance of different light sources with different S/P ratios in real field applications considering mesopic dimensioning.

1.6 Steps of execution

Step 1: Evaluation of Visual Adaptation Field

1.1. Studies on recent relevant research on the application of mesopic photometry system in outdoor lighting;

1.2. To examine the effect of light sources with different SPDs and off-axis object positions on perceived brightness in laboratory environments;

1.3. Simulation of adaptation luminance for different outdoor lighting applications;

1.4 Measurement of adaptation luminance in outdoor lighting conditions;

1.5 Comparison of the real field measurement data with simulated parameters.

Step 2: Evaluation of lamp performance

2.1. Evaluation of the photometric performance of different light sources with different S/P ratios;

2.2. Comparison of the performance of those light sources;

2.3. Determination of the energy-saving potential of retrofitting outdoor lighting with light sources with higher S/P ratio

1.7 Original contributions

Following are the original contributions of the proposed work:

- 1) The uniqueness of this present work is to study the variation in adaptation luminance due to surrounding light sources of different spectral compositions by comparing the adaptation luminance and the corresponding mesopic luminance under the variable surrounding luminance effect.
- 2) Identification of visually effective lighting designs for outdoor lighting applications which are supposed to be more energy efficient compared to the photopic aspect.
- 3) The outcome of the present work may be useful for the implementation of mesopic photometry and analysis of the performance of light sources with different S/P ratios considering mesopic dimensioning.

1.8 Organisation of the thesis

The details of the work done in the present thesis are organized as follows:

Chapter 1 contains a general introduction to the mesopic photometry system, literature review, present scenario, motivation for this research work, objective of the work, and organization of the project.

“Background Theory” behind this thesis work is discussed in **Chapter 2** which describes the general theory of mesopic photometry systems, details of outdoor lighting and the problem statement with its objectives.

Several light sources that are frequently employed in outdoor light-

ing applications and regarded as the main light source (MLS) have been used to replicate outdoor lighting conditions in **Chapter 3**. To achieve the effect of surrounding light sources on the application area in a real scenario, three surrounding light sources (SLSs) are also considered. Warm white SLE (WWSLE) and cool white SLE (CWSLE) are the two distinct situations for which these surrounding lighting effects (SLE) have been designed. MATLAB software was used to carry out the simulation.

In **Chapter 4**, outdoor lighting conditions have been developed in laboratory environments with different light sources which are commonly used in outdoor lighting applications. The photopic luminance for the entire field of measurement were measured and corresponding mesopic luminance values are calculated from CIE 191:2010 Table[1] using the scotopic/photopic (S/P) ratio of the lamps. Adaptation luminance for the said area of measurement is calculated by the method described in Chapter 2. Three surrounding light sources are also taken into consideration to achieve the effect of surrounding light sources in actual condition. These surrounding lighting effects (SLE) have been created for two different conditions same as discussed for Chapter 3.

Chapter 5 describes the experimentation to study the change in adaptation luminance due to various combinations of lamps of different spectral compositions and variable surrounding luminance effects caused by warm white and cool white light sources. According to the analysis of the experimental data, the effective adaption luminance should be taken into account for area measurements rather than mesopic luminance for an outdoor area subjected to variable luminance. The surrounding light sources' spectral composition has a major impact on the luminance adaption.

The conversion of the photopic luminous flux of the luminaire provided by the manufacturer into its equivalent mesopic luminous flux and the usage of DIALux 4.13 software to simulate average mesopic luminance values are the main topics of **Chapter 6**. The improvement in efficiency of lighting design is analyzed by comparing the simulated photopic luminance, computed mesopic luminance from CIE191:2010, and simulated mesopic luminance for different lamps.

The final chapter, **Chapter 7**, provides a conclusive appraisal of the importance and limitations of the current study as well as recommendations for the likely areas of future research.

The conceptual flow diagram of the thesis is shown in **Fig. 1.1**.

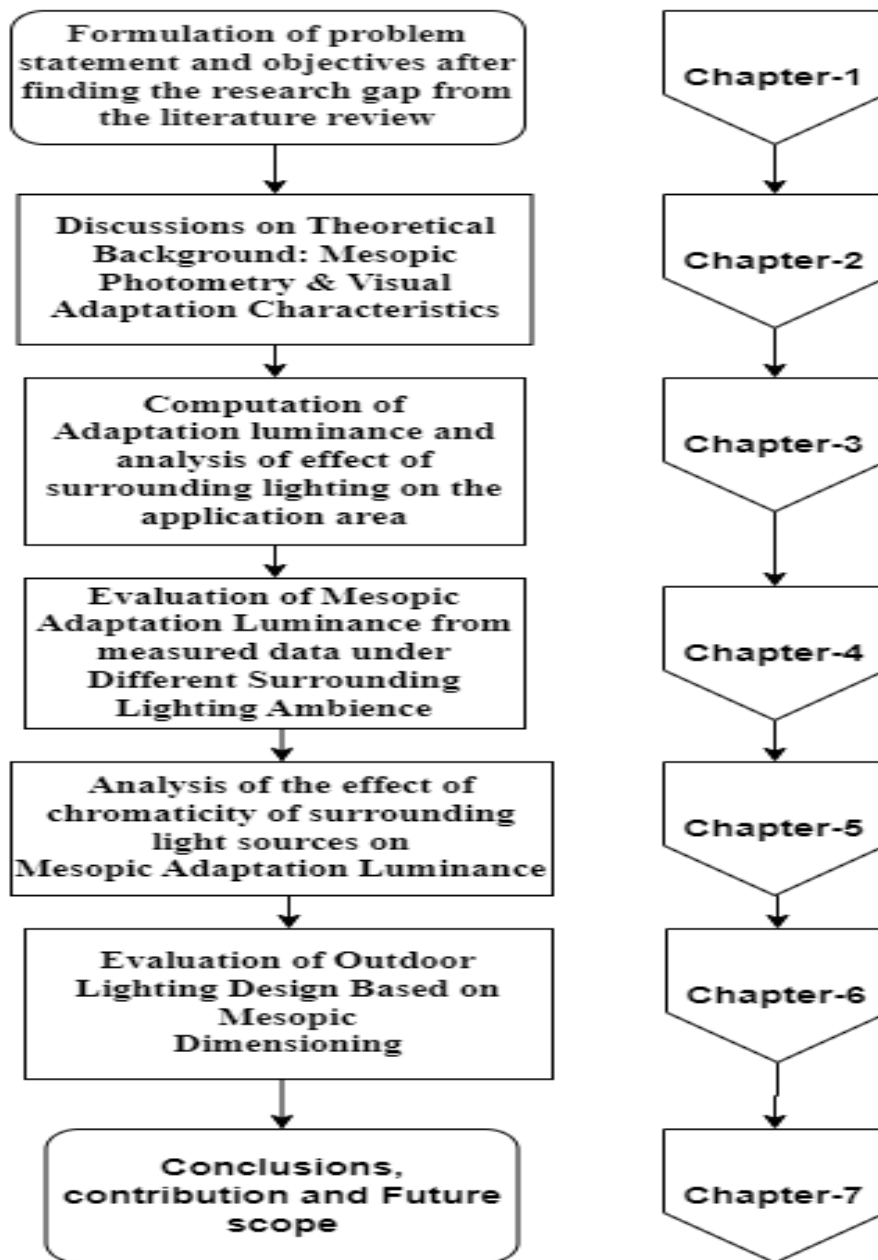


Fig. 1.1: Conceptual flow diagram of the thesis

2 Theoretical Background: Mesopic Photometry & Visual Adaptation Characteristics

This chapter provides a comprehensive overview of the general theory of mesopic photometry systems, including their application in outdoor lighting scenarios. Additionally, it delves into the specific challenges associated with outdoor lighting and presents the problem statement along with its corresponding research goals. The chapter also explores the 'Background Theory' that forms the foundation for this thesis work, ensuring a thorough understanding of the subject matter.

2.1 Introduction

Photometry is defined as the measurement of lighting parameters and refers to the optical radiation computed according to a given spectral luminous efficiency function based on human vision. Depending upon the participation of the two photo-sensitive cells of the human eye i.e. rod and cone, there are three types of vision as defined by the International Commission on Illumination (CIE) [1, 3]. At high adaptation levels i.e. when luminance is more than 5 cd/m^2 , the cone cells remain active and the human eye is subjected to photopic vision. At very low adaptation levels i.e. when luminance is below 0.005 cd/m^2 , only rods are active and it is termed as scotopic vision. For the intermediate adaptation levels i.e. when luminance is between 0.005 cd/m^2 and 5 cd/m^2 , both the cone and rod cells participate in vision and is called as mesopic vision. Various street and outdoor lighting applications have luminance levels subjected to mesopic vision.

2.2 Human Vision

As discussed previously depending upon the adaptation levels there are three types of vision:

- Photopic Vision
- Scotopic Vision
- Mesopic vision
- **Photopic Vision**

Under photopic vision, fine image and colour details of the objects are visible due to the presence of red, green and blue sensitive cones. These cone cells are concentrated at that part of the retina of eye which is used for on-line vision. The spectral sensitivity of human eye

under photopic vision is characterized by the $V(\lambda)$ curve and has the maximum sensitivity of 683 lumen/watt at wavelength of 555 nm [3] as shown in **Fig. 2.1**[1]. This region falls under the green-yellow region of the spectrum. At present, almost all the photometric parameters are measured in photopic region and based on the $V(\lambda)$ function.

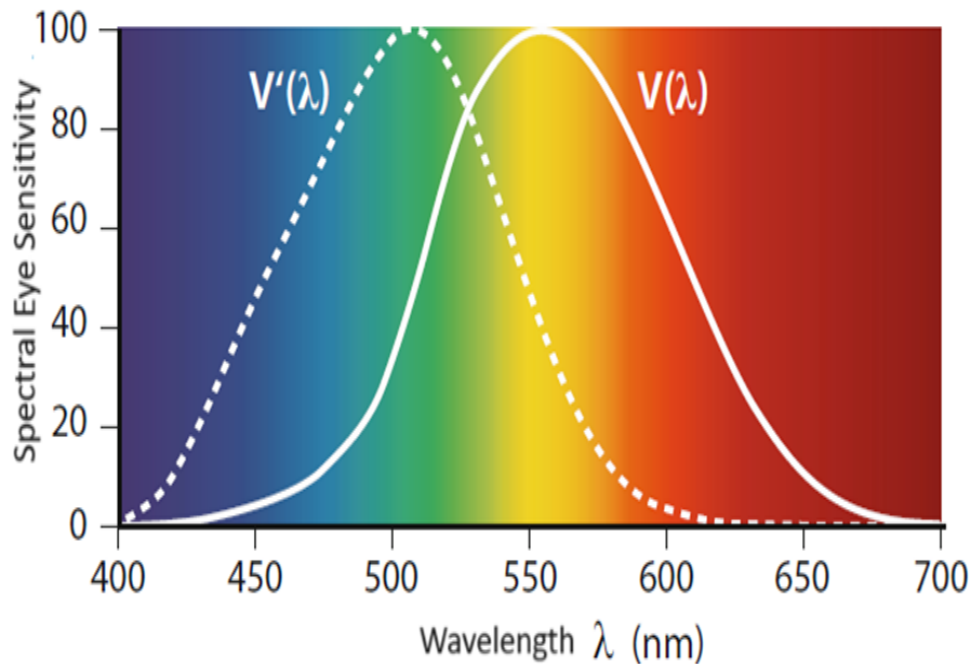


Fig. 2.1: Normalized Spectral sensitivity curves of human eye for photopic and scotopic vision

- **Scotopic Vision**

Unlike the photopic vision no colour details of the viewing object is available in scotopic vision. Rods are located only at peripheral locations of the retina that is used for peripheral vision. The spectral sensitivity is characterized by the $V'(\lambda)$ curve and has the maximum sensitivity of 1699 lumen/watt at a wavelength of 507 nm. This region falls under the blue-green region of the spectrum as shown in **Fig. 2.1**.

- **Mesopic Vision**

When the luminance level lies between approximately 0.005 and 5 cd/m^2 both the cone and the rod cells participate in vision and it is termed as mesopic vision. The peak sensitivity of human eye under mesopic vision gradually shifts from higher to lower wavelengths with the decrease in adaptation level as shown in **Fig. 2.2**.

Therefore, under mesopic region, the lamps with more bluish content in its spectrum are more visually effective than the light sources with more yellow content in its spectrum. On the other hand, as the cone cells are responsible for on-line vision and rod cells are more sensitive to short wavelengths in mesopic vision [1, 38, 39], the peripheral task performance is better with light sources with more blue light content in its spectrum.

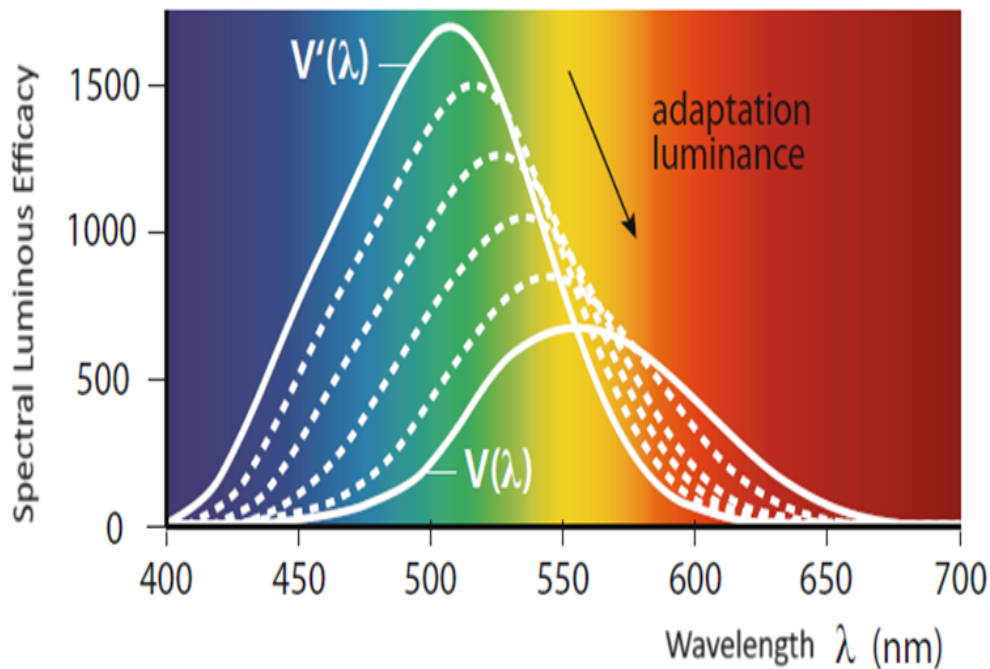


Fig. 2.2: Variation in spectral luminous efficacy curves for mesopic vision

- **On-Line and Off-Line Vision**

The density of cone and rod cells in the retina of eye is not uniform. Cones are mostly concentrated in the foveal region and rod cells are

on the outer or peripheral region of retina. Sharp image of viewing object is formed in a narrow field of view of 2° centered around the line of vision. Rods are not available in this foveal region. However, presence of cones diminishes outside the fovea very rapidly as shown in **Fig. 2.3**[1].

Therefore, cone cells are responsible for foveal vision. This is also known as “central” or “on-line” vision. The spectral sensitivity for this type of vision is the $V(\lambda)$ function and it is applicable for measurement in photopic as well as mesopic region [3]. Despite the small field of view, colour image is formed of a larger area as the eyes shift gaze continuously from one fixation point to another within the entire field of view. Part of these fixation-point changes i.e. saccades, are stepwise and occurs within very short time i.e. between 0.04 and 0.2 second [1]. The duration time of one such fixation is almost 0.25 second and during these movements no image is formed. The density of rod cells is maximum at about 15° from the direction of view as shown in **Fig. 2.3**. Therefore, rod cells are responsible for “offline” or “peripheral” vision and the peripheral image that is created is blurred [40].

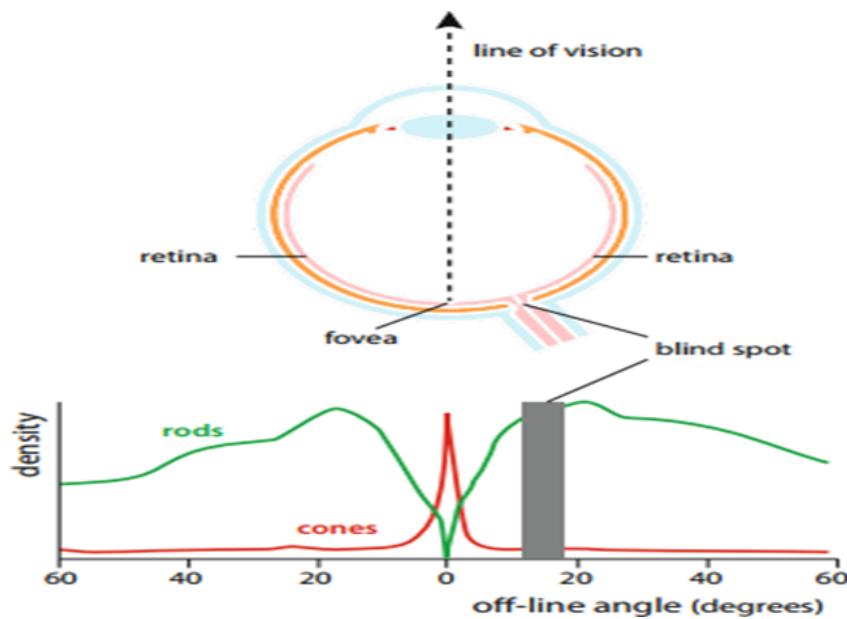


Fig. 2.3: Density of cones and rods in the retina of human eye [1]

2.3 S/P Ratio of Light Source

The term “scotopic to photopic ratio,” or S/P ratio, refers to the ratio of the luminous flux output calculated using the scotopic spectral luminous efficiency function $V'(\lambda)$ to the luminous flux calculated using photopic spectral luminous efficiency function $V(\lambda)$. The expression is shown in **Eq. 2.1**.

$$S/P\text{Ratio} = \frac{K'_m \int S_\lambda(\lambda) V'(\lambda) d\lambda}{K_m \int S_\lambda(\lambda) V(\lambda) d\lambda} \quad (2.1)$$

where:

K'_m is the maximum luminous efficacy for scotopic vision ($K'_m = 1699$ lm/W).

K_m is the maximum luminous efficacy for photopic vision ($K_m = 683$ lm/W),

$S_\lambda(\lambda)$ is the spectral distribution of light source,

λ is the wavelength.

To quantify the effect of the spectrum of a lamp on peripheral vision in the mesopic luminance range, the amount of radiation in the photopic and scotopic range must be determined. The S/P ratio can be computed from the SPD of the light source. The S/P ratios of light sources used in outdoor lighting are shown in **Table 2.1** [27].

2.4 Mesopic System Model

The CIE has defined specific $[V(\lambda)]$ and $[V'(\lambda)]$ curves for photopic and scotopic vision respectively, but there was no established function for mesopic vision until few years ago. The research to find the spectral luminous efficiency function for mesopic vision was based on brightness matching criterion between the target object and the surface adjacent to it till mid-1990s [3]. After that detection and recognition of the

Table 2.1: Typical S/P ratios of different light source

Light Source	S/P Ratio
Low Pressure Sodium Vapour (LPSV)	0.23
High Pressure Sodium Vapour (HPSV)	0.4
Mercury Vapour	0.8
Incandescent	1.41
Quartz Halogen	1.5
Fluorescent	1.5-2.4
Cool White LED	2.3
Red LED (635 nm)	0.06
Blue LED 470 Nm)	14.3

object became much more relevant as visual task performance experiments was the criterion instead of brightness matching.

CIE has published a recommendation for a performance based mesopic photometry system CIE 191:2010 which provides a bridge between the scotopic and photopic photometry system. It's development has prioritised the visual performance for applications involving street and road lighting. According to the CIE 191 system, mesopic luminous efficiency function $V_{mes}(\lambda)$ is a linear combination of the photopic $V(\lambda)$ and scotopic $V'(\lambda)$ luminous efficiency functions.

- **Brief Description of Mesopic Models**

There is a long research history behind the development of mesopic spectral sensitivity functions [41–53]. These previous studies have suggested some spectral sensitivity function based on adaptation light level in the mesopic region. In 1989, the CIE published one model for mesopic vision and the updated version of this model was published in 2001 [49, 50]. Few mesopic models and their most important parameters are shown in **Table 2.2** [54].

2.4.1 Visual Task Performance Based Approach

The basis for this photometric system is the empirical visual performance data using human subjects. Considering different factors that

Table 2.2: A list of Mesopic models

No	Model	Field Diameter (Degree)	Eccentricity (Degrees)	Input Variables
1	Palmer 1	10	0	L_{10}, L'
2	Palmer 2	10	0	L_{10}, L'
3	Sagawa-Takeichi	10	0	L_{10}, L', X, Y, Z
4	Nakano-Ikeda	10	0	$L', X_{10}, Y_{10}, Z_{10}$
5	Kokoschka- Bodmann	10	0	$L', X_{10}, Y_{10}, Z_{10}$
6	Trezona	10	0	$L', X_{10}, Y_{10}, Z_{10}$
7	Ashizawa	10	0	$V_{10}(\lambda), V'(\lambda)$
8	He 1	2	15	$L_e(\lambda)$
9.	He 2	2	12	$L_e(\lambda)$
10	Rea	2	Non-foveal	$L_e(\lambda)$
11	Uniff	2	Non-foveal	L_e, L

can affect the human vision, such as shape and position of the object within the field of vision, light level and the spectral characteristics of the source, speed, a CIE Technical Committee provided one equation for the mesopic vision considering both the $V(\lambda)$ and $V'(\lambda)$ functions. The expression for the spectral sensitivity function, $V_{mes}(\lambda)$ is shown in **Eq. 2.2**.

$$V_{mes}(\lambda) = yV(\lambda) + (1 - y)V'_\lambda \quad (2.2)$$

where:

y is the adaptation coefficient

Here the mesopic spectral sensitivity functions, $V_{mes}(\lambda)$ is additive in nature but only within a given adaptation level. From the above approach two systems for mesopic photometry were developed, these are the USP (Unified System of photometry) system [16] and the MOVE (Mesopic Optimisation of the Visual Efficiency) system [10]. An Intermediate system is also considered to bridge the gap between these two systems.

- **The USP System**

Experiments were conducted and reaction times were recorded at varying luminance levels in the Unified System of Photometry (USP) system between 0.003 cd/m^2 and 10 cd/m^2 . The SPD of the target point and the backgrounds were same. In this system the spectral sensitivity function is considered as a linear combination of the 10^0 photopic $[V_{10}(\lambda)]$ and scotopic $[V'_{10}(\lambda)]$ functions and expressed by the **Eq. 2.3** for $0 \leq X \leq 1$ [16].

$$V_{mes}(\lambda) = XV(\lambda) + (1 - X)V'_\lambda \quad (2.3)$$

In this system 0.6 cd/m^2 was the limiting value between the photonic and mesopic luminance level. The adaptation coefficient X and mesopic luminance were assumed to be linear between 0.001 cd/m^2 and 0.6 cd/m^2 . $V_{10}(\lambda)$ was substituted by $V(\lambda)$, as the photometric quantities calculated based on $V(\lambda)$ and $V_{10}(\lambda)$ are almost same. The mesopic luminance L_{mes} and X can be calculated for $0.001 < L_{mes} < 0.6$ and $0 \leq X \leq 1$ using **Eq.2.4** and **Eq.2.5** as shown below.

$$L_{mes} = 0.834L_p - 0.335L_s - 0.2 + \sqrt{0.696L_p^2 - 0.333L_p - 0.56L_pL_s + 0.113L_s^2 + 0.537L_s + 0.04} \quad (2.4)$$

$$X = mL_{mes} + \beta \quad (2.5)$$

where:

L_p is the photopic luminance,

L_s is the scotopic luminance,

m is coefficient given by $m = 1/0.599$ and

$\beta = -30.001/0.599$ [16]

Table 2.3: X as a function of photopic luminance and S/P-ratio for USP System

	S / P	Photopic luminance cd/m ²						
		0.0010	0.0030	0.0100	0.0300	0.1000	0.3000	0.5500
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	
MH warm white ~	1.05	0.0001	0.0036	0.0158	0.0506	0.1707	0.5061	0.9181
	1.15	0.0002	0.0041	0.0174	0.0549	0.1814	0.5194	0.9211
	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
MH day light	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
	2.35	0.0022	0.0099	0.0356	0.1012	0.2798	0.6287	0.9449
	2.45	0.0024	0.0104	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

The values of X and mesopic luminance L_{mes} in this system are shown in **Table 2.3** and **Table 2.4** [16] as a function of photopic luminance and S/P-ratio of a light source.

• The MOVE System

An empirical multi-technique approach serves as the foundation for the Mesopic Optimisation of the Visual Efficiency (MOVE) system [10]. Here, a task like driving at night was broken down into three visual subtasks: identifying the specifics of the target, detecting a visual target, and detecting a target [3]. Reaction times influence the detection speed [55, 56]. In this MOVE system, the mesopic spectral sensitivity function is expressed by **Eq. 2.6** for $0 \leq x \leq 1$ [38].

$$M(x)V_{mes}(\lambda) = xV(\lambda) + (1 - x)V_{\lambda}' \quad (2.6)$$

where:

Table 2.4: Mesopic Luminance as a function of photopic luminance and S/P-ratio for USP System

	S / P	Photopic luminance cd/m ²						
		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	0.056	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	0.542
	0.75	0.0007	0.0023	0.0078	0.0231	0.0820	0.2758	0.5446
	0.85	0.0008	0.0026	0.0085	0.0259	0.0895	0.2882	0.5469
	0.95	0.0009	0.0028	0.0095	0.0288	0.0986	0.2956	0.549
MH	1.05	0.0010	0.0031	0.0105	0.0313	0.1033	0.3042	0.5509
	1.15	0.0011	0.0034	0.0114	0.0339	0.1096	0.3121	0.5527
	1.25	0.0012	0.0037	0.0124	0.0365	0.1157	0.3196	0.5544
white ~	1.35	0.0013	0.0040	0.0133	0.039	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	0.0018	0.0049	0.0161	0.0462	0.1374	0.3448	0.56
	1.75	0.0017	0.0052	0.017	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	0.053	0.1517	0.3602	0.5633
	2.05	0.0020	0.0061	0.0197	0.0552	0.1561	0.3846	0.5643
	2.15	0.0021	0.0064	0.0206	0.0574	0.1604	0.3893	0.5653
	2.25	0.0022	0.0067	0.0215	0.0595	0.1646	0.3736	0.5662
MH day light ~	2.35	0.0023	0.0069	0.0224	0.0618	0.1886	0.3776	0.567
	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	0.1783	0.3852	0.5686
	2.65	0.0026	0.0078	0.0249	0.0667	0.18	0.3888	0.5693
	2.75	0.0027	0.0081	0.0258	0.0697	0.1836	0.3923	0.57

Table 2.5: Values of x in MOVE system as a function of photopic luminance and S/P-ratio

	S / P	Photopic Luminance cd/m ²						
		0.01	0.03	0.1	0.3	1	3	10
LPS -	0.25		0	0.308	0.4900	0.6660	0.8160	0.972
	0.35		0.07	0.32	0.495	0.6690	0.8170	0.972
	0.45		0.109	0.33	0.501	0.6710	0.818	0.972
HPS ~	0.55		0.1330	0.3400	0.505	0.6740	0.819	0.972
	0.65		0.151	0.348	0.51	0.676	0.8200	0.972
	0.75		0.166	0.355	0.514	0.678	0.8210	0.972
	0.85	0.0000	0.1780	0.3620	0.518	0.68	0.822	0.973
	0.95	0.0120	0.189	0.368	0.522	0.6830	0.823	0.973
MH warm white ~	1.05	0.028	0.198	0.374	0.526	0.685	0.824	0.973
	1.15	0.041	0.207	0.379	0.529	0.687	0.825	0.973
	1.25	0.0530	0.215	0.384	0.532	0.6880	0.826	0.973
	1.35	0.063	0.222	0.389	0.536	0.89	0.8270	0.973
	1.45	0.072	0.229	0.394	0.5390	0.692	0.8280	0.973
	1.55	0.081	0.235	0.398	0.542	0.694	0.829	0.9740
	1.65	0.088	0.241	0.402	0.5440	0.8960	0.83	0.974
	1.75	0.096	0.246	0.406	0.5470	0.6970	0.831	0.974
	1.85	0.1020	0.251	0.41	0.55	0.099	0.832	0.974
	1.95	0.1080	0.256	0.413	0.552	0.7	0.8320	0.9740
MH day light	2.05	0.1140	0.261	0.416	0.5550	0.702	0.8330	0.974
	2.15	0.12	0.265	0.42	0.557	0.7040	0.8340	0.974
	2.25	0.125	0.269	0.423	0.559	0.7050	0.835	0.974
	2.35	0.1300	0.273	0.426	0.562	0.7060	0.8360	0.975
	2.45	0.135	0.277	0.429	0.564	0.7080	0.836	0.975
	2.55	0.1390	0.281	0.432	0.566	0.709	0.8370	0.975
	2.65	0.1440	0.284	0.434	0.568	0.7110	0.8380	0.975
2.75	0.1480	0.288	0.4370	0.5700	0.7120	0.839	0.975	

Table 2.6: Mesopic Luminance given by the MOVE system as a function of photopic luminance and S/P-ratio

	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	0.064	0.234	0.8740	2.81	9.9100
	0.35	0.0035	0.0136	0.0700	0.243	0.892	2.84	9.9300
	0.45	0.0045	0.0173	0.075	0.253	0.91	2.88	9.94
HPS ~	0.55	0.0055	0.0202	0.08	0.262	0.927	2.89	9.95
	0.65	0.0065	0.0227	0.085	0.271	0.943	2.91	9.9000
	0.75	0.0075	0.025	0.089	0.279	0.9600	2.94	9.97
	0.85	0.0085	0.0271	0.094	0.288	0.9760	2.98	9.9800
	0.95	0.0095	0.0291	0.098	0.296	0.992	2.99	9.9900
	1.05	0.0105	0.0309	0.102	0.304	1.008	3.01	10.0100
MH warm white ~	1.15	0.0114	0.0327	0.1	0.312	1.023	3.04	10.02
	1.25	0.0122	0.0345	0.11	0.32	1.038	3.06	10.03
	1.35	0.0130	0.0361	0.114	0.327	1.0530	3.08	10.04
	1.45	0.0138	0.0378	0.117	0.335	1.068	3.1000	10.0500
	1.55	0.0145	0.0394	0.121	0.342	1.083	3.13	10
	1.65	0.0152	0.0409	0.124	0.349	1.097	3.15	10.0700
	1.75	0.0159	0.0424	0.128	0.356	1.111	3.17	10.08
	1.85	0.0166	0.0439	0.131	0.363	1.125	3.1900	10.09
	1.95	0.0173	0.0454	0.135	0.37	1.1390	3.2100	10.1000
	2.05	0.0179	0.0468	0.138	0.377	1.153	3.23	10.1100
	2.15	0.0186	0.0482	0.141	0.384	1.167	3.26	10.12
	2.25	0.0192	0.0496	0.144	0.39	1.18	3.2800	10.13
MH day light	2.35	0.0198	0.0509	0.147	0.397	1.193	3.3000	10.14
	2.45	0.0205	0.0523	0.1510	0.403	1.206	3.32	10.15
	2.55	0.0211	0.0536	0.1540	0.41	1.219	3.34	10.16
	2.65	0.0218	0.0549	0.157	0.416	1.232	3.36	10.17
	2.75	0.0222	0.0562	0.16	0.422	1.245	3.3800	10.1800

$M(x)$ is a normalizing function when the value of $V_{mes}(\lambda)$ is maximum i.e. 1,

$V_{mes}(\lambda)$ is the mesopic spectral luminous efficiency function,
 x is the adaptation coefficient.

The upper limit for the MOVE system is up to 10 cd/m² and the lower limit for mesopic is 0.01cd/m². The values of the adaptation coefficient x and mesopic luminance, L_{mes} in this system can be computed as shown below using **Eq.2.7** and **Eq.2.8** for $0 \leq x \leq 1$.

$$x_{n+1} = a + b \log_{10} \left[\frac{1}{M(x_n)} \left(x_n \frac{L_p}{K_p} + (1 - x_n) \frac{L_s}{K_s} \right) \right] \quad (2.7)$$

$$L_{mes} = \frac{xL_p + (1 - x)L_s V'(\lambda_0)}{x + (1 - x)V'(\lambda_0)} \quad (2.8)$$

where:

$$a=1.49$$

$$b=0.282$$

K_p is the photopic maximum luminous efficacy ($K_p = 683 \text{ lm}\cdot\text{W}^{-1}$),

K_s is the scotopic maximum luminous efficacy ($K_s = 1699 \text{ lm}\cdot\text{W}^{-1}$),

L_{mes} is the mesopic luminance,

$$V'(\lambda_0) = 683/1699 \text{ and}$$

n is an iteration step.

The normalizing function $M(x)$ can be computed using **Eq.2.9**.

$$M(x) = \max[xV(\lambda) + (1 - x)V'(\lambda)] \approx 1 - 0.65x + 0.65x^2 \quad (2.9)$$

The values of x and L_{mes} in this system as a function of photopic luminance and S/P ratio of lamps are shown in **Table 2.5** and **Table 2.6**.

• The Intermediate System

The difference in the computed mesopic luminance as a function of photopic luminance in the USP and MOVE systems is higher in case of highly coloured sources at low luminance levels. But the difference is small for almost all the white light sources. For the USP-system, the transition from mesopic system to the photopic system occurs at $0.6 \text{ cd}/\text{m}^2$. The MOVE-system considers scotopic spectral luminous efficiency function up to $10 \text{ cd}/\text{m}^2$. As the upper and lower limit of luminance is too high in the MOVE system [16] and too low in case of USP-system [38], for the Intermediate system between these two systems, the upper and lower limit of luminance is definite [57].

This system with upper and lower limits of $3 \text{ cd}/\text{m}^2$ and $0.01 \text{ cd}/\text{m}^2$, and showed as the MES1-system in **Eq.2.10** below.

$$M(m_1)V_{mes}(\lambda) = m_1V(\lambda) + (1 - m_1)V'(\lambda) \quad (2.10)$$

where:

$M(m_1)$ is a normalizing function

If $L_{mes} \geq 3.0 \text{ cd/m}^2$, then $m_1=1$.

If $L_{mes} \leq 0.01 \text{ cd/m}^2$, then $m_1=0$.

If $0.01 \text{ cd/m}^2 < L_{mes} < 3.0 \text{ cd/m}^2$, then $m_1=0.404 \log L_{mes} + 0.807$

The coefficient m_1 and L_{mes} can be computed using **Eq.2.11** and **Eq.2.12** for $0 \leq m_{1,n} \leq 1$.

$$L_{mes,n} = \frac{m_{1,(n-1)}L_p + (1 - m_{1,(n-1)})L_sV'(\lambda_0)}{m_{1,(n-1)} + (1 - m_{1,(n-1)})V'(\lambda_0)} \quad (2.11)$$

$$m_{1,n} = a + b \log_{10}(L_{mes,n}) \quad (2.12)$$

where:

$$a=0.807$$

$$b=0.404$$

The values of m_1 and L_{mes} given by the MES1-system as a function of photopic luminance and light source S/P-ratio are shown in **Table 2.7** and **Table 2.8** below.

The Intermediate system considers the upper and lower limit of luminance as 5 cd/m^2 and 0.005 cd/m^2 respectively and denoted as MES2-system as shown in **Eq.2.13** below.

$$M(m_2)V_{mes}(\lambda) = m_2V(\lambda) + (1 - m_2)V'(\lambda) \quad (2.13)$$

where:

$M(m_2)$ is a normalizing function.

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

If $L_{mes} \leq 0.0005 \text{ cd/m}^2$, then $m_2=0$.

If $0.005 \text{ cd/m}^2 < L_{mes} < 5.0 \text{ cd/m}^2$, then $m_2=0.3334 \log L_{mes} + 0.767$

The coefficient m_2 and the mesopic luminance L_{mes} obtained using the MES1-system can be iteratively computed using **Eq.2.14** and **Eq.2.15** for $0 \leq m_{2,n} \leq 1$.

$$L_{mes,n} = \frac{m_{2,(n-1)}L_p + (1 - m_{2,(n-1)})L_s V'(\lambda_0)}{m_{2,(n-1)} + (1 - m_{2,(n-1)})V'(\lambda_0)} \quad (2.14)$$

$$m_{2,n} = a + b \log_{10}(L_{mes,n}) \quad (2.15)$$

where:

$$a=0.767$$

$$b=0.3334$$

The values of m_2 and L_{mes} given by the MES1-system as a function of photopic luminance and light source S/P-ratio are shown in **Table 2.9** and **Table 2.10** below.

2.4.2 CIE Mesopic Photometry System-CIE191:2010

Finally in 2010, CIE has published the recommended system for visual performance-based mesopic photometry and the spectral luminous ef-

Table 2.7: Values of m_1 given by the MES1-system as a function of photopic luminance and S/P-ratio

	S / P	Photopic luminance cd /m2							
		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	0.345	0.5867	0.796	0.925	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	0.803	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	0.207	0.4123	0.6012	0.8093	0.9294	1	
	1.25	0.0352	0.216	0.4181	0.6047	0.8107	0.9299	1	
	1.35	0.0466	0.2243	0.4235	0.608	0.8121	0.9304	1	
	1.45	0.0569	0.2319	0.4286	0.6111	0.8135	0.9309	1	
	1.55	0.0663	0.239	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	0.62	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	0.82	0.9332	1	
	2.05	0.1036	0.2685	0.4546	0.628	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	0.633	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	0.475	0.6421	0.828	0.9362	1	
2.75		0.1408	0.2995	0.4781	0.6442	0.8291	0.9366	1	
2.85		0.1452	0.3033	0.481	0.6463	0.8301	0.937	1	
2.95		0.1494	0.3069	0.4838	0.6483	0.8311	0.9373	1	

efficiency function for mesopic region, $V_{mes}(\lambda)$ has been considered as a linear combination of $V(\lambda)$ and $V'(\lambda)$ functions [3]. The spectral luminous efficiency function can be expressed using **Eq.2.16** and **Eq.2.17** for $0 \leq m \leq 1$.

$$M(m)V_{mes}(\lambda) = mV(\lambda) + (1 - m)V'(\lambda) \quad (2.16)$$

$$L_{mes} = \frac{683}{V_{mes}(\lambda_0)} \int V_{mes}(\lambda)L_e(\lambda)d\lambda \quad (2.17)$$

where:

$M(m)$ is a normalizing function such that the mesopic spectral luminous efficiency function, $V_{mes}(\lambda)$ attains a maximum value of 1, is the spectral radiance in $W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}$

Table 2.8: Values of L_{mes} given by the MES1-system as a function of photopic luminance and S/P-ratio

S / P		Photopic luminance cd/m ²						
		0.01	0.03	0.1	0.3	1	2	3
LPS -	0.25	0.0025	0.0075	0.0864	0.2462	0.9292	1.9522	3
	0.35	0.0035	0.0118	0.0719	0.2541	0.9393	1.9590	3
HPS ~	0.45	0.0045	0.0167	0.0769	0.2618	0.9492	1.9656	3
	0.55	0.0055	0.0199	0.0816	0.2892	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	0.9887	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
MH day light	2.25	0.0194	0.0491	0.1399	0.3709	1.0991	2.0685	3
	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

Table 2.9: Values of m_2 given by the MES2-system as a function of photopic luminance and S/P-ratio

S / P		Photopic Luminance cd/m ²						
		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
HPS ~	0.45	0.0000	0.1992	0.4000	0.5730	0.7578	0.9235	0.9843
	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	0.3128	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
MH day light	2.25	0.1852	0.3245	0.4801	0.6242	0.7840	0.9312	0.9858
	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

Table 2.10: Values of L_{mes} given by the MES2-system as a function of photopic luminance and S/P-ratio

	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
	0.55	0.005 7	0.022 0	0.083 4	0.269 3	0.949 2	2.956 8	4.487 2
HPS -	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
MH warm white ~	1.05	0.010 4	0.030 8	0.101 7	0.303 2	1.005 4	3.004 6	4.501 4
	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
MH day light ~	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
	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	0.0200	7 0.052 9	0.1510	1 0.398 9	1.169 3	3.147 3	4.544 1

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

If $L_{mes} \leq 0.0005cd/m^2$, then $m=0$.

The m and L_{mes} can be obtained using **Eq.2.18** and **Eq.2.19** for $0 \leq m \leq 1$.

$$L_{mes,n} = \frac{m_{(n-1)}L_p + (1 - m_{(n-1)})L_s V'(\lambda_0)}{m_{(n-1)} + (1 - m_{(n-1)})V'(\lambda_0)} \quad (2.18)$$

$$m_n = a + b \log_{10}(L_{mes,n}) \quad (2.19)$$

where:

$$a=0.767$$

$$b=0.3334.$$

Table 2.11: Adaptation Coefficient m as a function of photopic luminance and S/P-ratio of lamps

	S / P	Photopic Luminance		cd/m ²				
		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
MH warm white ~	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
	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
MH day light -	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
	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	

The values of m and L_{mes} for this system as a function of photopic luminance and light source S/P-ratio are given in **Table 2.11** and **Table 2.12**.

2.5 Visual Adaptation Field and Adaptation Luminance

The field of vision, also known as the visual field, is defined by the CIE as the “extent of space in which objects are visible to an eye in a given position” [58, 59]. According to the Society of Automotive Engineers (SAE), the visual field, is “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” [60]. Again, the term adaptation refers to the process through which exposure to stimuli with varying brightness values, spectral distributions, and angular subtense in the past and present modifies the state of the visual system. The “state of the visual system after an adaptation process

Table 2.12: Values of L_{mes} as a function of photopic luminance and S/P-ratio

LPS -	S/P	Photopic		Luminance		cd/m ²		
		0.01	0.03	0.1	0.3	1	3	4.5
HPS ~	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
	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
	MH warm white ~	1.05	0.0104	0.0308	0.1017	0.3032	1.0054	3.0046
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
MH day light	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
	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

has been completed” is known as the state of adaptation [59]. The field of visual adaption is dependent on the lighting and how other road users behave when driving and walking in different conditions. The actual spectral visual response function of an observer is difficult to determine because it depends on a wide range of complex factors, including the number, kind, size, and spatial distribution of light sources within the field of view, the observer’s gaze direction and eye movements around it, observer’s age; and the nature of the visual task. These issues arise whenever a photometric measurement or computation is conducted, regardless of whether mesopic photometry is the focus or not. Due to this complexity, assumptions and simplifications are considered and the spectrum luminous efficiency function that is selected is only a rough representation of the true visual response [58]. But in case of the mesopic system, such simplification is not possible as the visual weighting function must be calculated according to the vi-

sual adaptation conditions, lamps and the environment. As described in the previous chapter various research on the adaptation state find that the local luminance of the application area is the main determinant of the adaptation state, but the surrounding luminance has some effects [7, 18, 61].

Mesopic luminous efficiency functions are defined by the mesopic photometry system in CIE 191:2010; the spectral efficiency of these functions varies based on the luminance of the observer's adaptation. Although the mesopic photometry system will increase the efficacy and efficiency of outdoor lighting design, there is still no standard way to apply it in actual outdoor lighting applications. Since the mesopic photometry system was created based on peripheral tasks, the adaptation luminance should be computed depending on the observers' peripheral adaptation condition [2].

2.5.1 Factors related to the adaptation luminance

The adaptation luminance of any real outdoor area has complex luminance distributions (LDs) as the real lit scenes are subjected to non-uniform road surface illuminance, sources with high luminance such as luminaires, and also the dark sky. The adaptation luminance in mesopic vision can be influenced by the following factors:

$L_e(\lambda)$ Eye movements (EMs)

- Surrounding luminance effect (SLE)
- Luminance distributions (LDs)
- Area of measurement (AOM)

Two coordinate systems are presented to consider the four characteristics and their derivatives as distribution functions in the field of vision [2]. A spherical coordinate system (θ, ϕ) , where θ is the horizontal angle and ϕ is the vertical angle, is one coordinate system known as the

“retinal coordinate system” that is used to display the location on the retina. As seen in **Fig. 2.4**, an additional coordinate system known as the “object coordinate system” is likewise spherical and has the same structure with distinct symbols (θ', ϕ') but is fixed to position outside rather than to the observer’s visual field. At the observer’s eye’s location, both coordinate systems have the same origin. The position $(\theta, \phi)=(0,0)$ in the retinal coordinate system corresponds to a peripheral point in the field of view. When an observer focuses at an “original point” in the object coordinate system, the position $(\theta', \phi')=(0,0)$ in the object coordinate system corresponds to the point $(\theta, \phi)=(0,0)$ in the retinal coordinate system. The retinal coordinate system tracks the movement of the observer’s line of sight, whereas the object coordinate system does not.

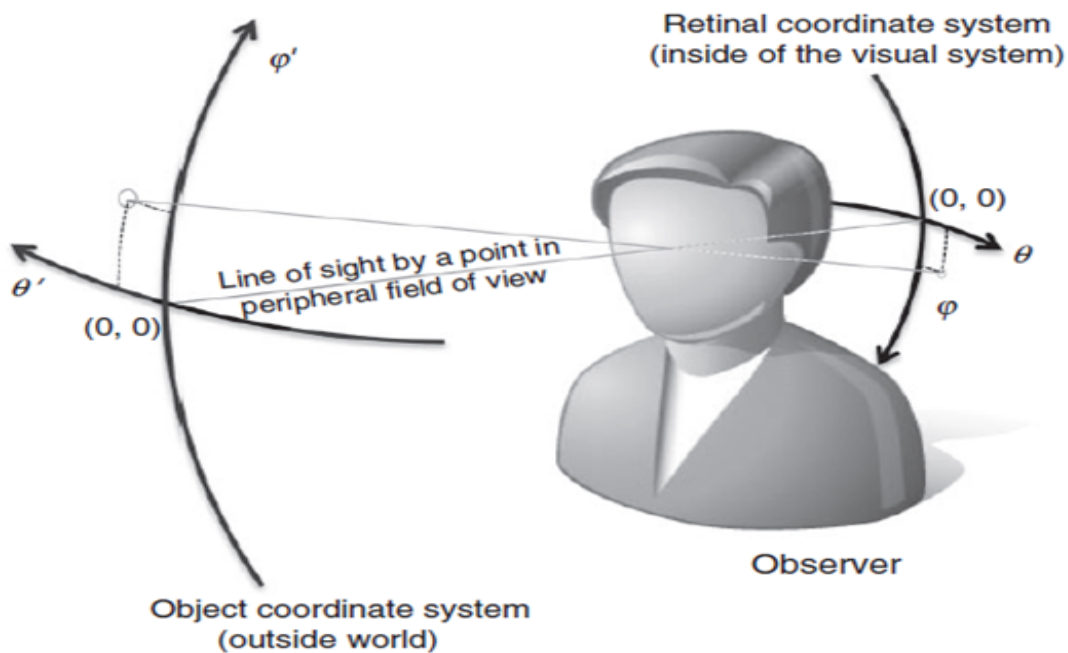


Fig. 2.4: Object coordinate system and retinal coordinate system [2]

- **Luminance distribution**

The adaption brightness is influenced by the luminance distribution (LD) of a lighted scene. In general, outdoor lighting has a broad range

of luminance at night than indoor space. The CIE 115:2010 [4] and other outdoor lighting guidelines prescribe an average brightness of 0.3 to 2.0 cd/m². The recommendations allow for a certain amount of non-uniformity, therefore the minimum luminance—typically at the edge of lighted areas may be 0.1 cd/m². However, the same scene may contain multiple light sources with high luminous intensity, such as headlights of approaching cars, or glowing signage etc. Certain luminaires, for instance, have a brightness of more than 10,000 cd/m². LD is defined by the luminance level function $L(\theta', \phi')$ with regard to the object coordinate system (θ', ϕ') .

- **Surrounding luminance effect**

The surrounding luminance effect (SLE) is caused due to the presence of surrounding light sources with the field of view of the observer. This effect, known as "veiling luminance," affects foveal vision and has been studied for a long time. The term "angular characteristic" refers to the increase in luminance as a function of the visual angle between a source of veiling luminance and the fovea. This phenomenon has been modelled by a number of equations, including the Stiles-Holladay formula [62] and the CIE general disability glare equation [63]. The mesopic photometry system relies on peripheral task performances, hence it is important to define and take into account SLE for peripheral vision. The peripheral SLE may be marginally higher than the foveal veiling luminance, according to earlier research. According to the Stiles-Crawford formula [64, 65], veiling luminance is described by the following equation **Eq.2.20**.

$$L_{veil} = \frac{16}{\theta_d^2} E_n \quad (2.20)$$

where:

E_n is the illuminance at the observer's eye on a plane perpendic-

ular to the direction from a surrounding source,
 θ_d is the visual angle between the source and a task point expressed in degrees.

The model provided by Uchida and Ohno [18] is shown below in **Eq.2.21**.

$$L_{veil} = \frac{260}{\theta^3} E_v \quad (2.21)$$

where:

E_v is the vertical illuminance caused by surrounding source,
 θ is the angle between the line of fixation and the high-luminance source.

Since the difference between E_n and E_v is negligible in a practical field of view, those models can generally be expressed by **Eq.2.22**.

$$L_{veil} = \frac{k}{\theta_d^n} E_n \quad (2.22)$$

In addition to being used to predict SLE at a task point from a surrounding source, this model can be transformed into a function to predict SLE for a surrounding area due to a point source. SLE [$f_{SLE}(\theta, \phi)$] caused by a small square source with 1 cd/m^2 of luminance, the size of which is $d\theta X d\phi$ can be derived from **Eq.2.23** and **Eq.2.24** as below:

$$f_{SLE}(\theta, \phi) = \frac{k}{\theta_d^n} E_n \quad (2.23)$$

where,

$$\theta_d = \tan^{-1} \sqrt{\tan^2 \theta + \tan^2 \phi} \quad (2.24)$$

$$d\omega = 4 \sin^{-1} \left(\sin \frac{d\theta}{2} \sin \frac{d\phi}{2} \right) \quad (2.25)$$

where:

$f_{SLE}(\theta, \phi)$ is a function in the retinal coordinate system for the surrounding source,

$d\omega$ is the solid angle due to small source in the retinal coordinate system as shown in **Eq.2.25**,

$f_{SLE}(\theta, \phi)$ can be described by **Eq.2.26**.

$$f_{SLE}(\theta, \phi) = \frac{1 - \iint_{D_{out}} f_{SLE}(\theta, \phi) d\theta d\phi}{\iint_{D_{in}} d\theta d\phi} \quad (2.26)$$

Where,

$$D_{out} = \{(\theta, \phi) \mid \theta_d \geq \theta_{d,th}\}$$

$$D_{in} = \{(\theta, \phi) \mid \theta_d < \theta_{d,th}\}$$

• Eye Movement

In a study, the Eye Movements are modeled as a two-dimensional (2D) Gaussian probability density distribution $f_{EM}(\theta', \phi')$ with no correlation [2] and defined by **Eq.2.27**.

$$f_{EM}(\theta', \phi') = \frac{1}{2\pi\sigma_{\theta'}\sigma_{\phi'}} * \exp \left[-\frac{1}{2} \left\{ \left(\frac{\theta'}{\sigma_{\theta'}} \right)^2 + \left(\frac{\phi'}{\sigma_{\phi'}} \right)^2 \right\} \right] d\theta' d\phi' \quad (2.27)$$

where:

$\sigma_{\theta'}, \sigma_{\phi'}$ are standard deviations (SD) for the horizontal and vertical directions.

The object coordinate system is taken into consideration when defining this function. It is important to remember that the EM function only describes the relative movement of the line of sight because it is centred

at the object coordinate system's origin [2]. A review of previous research on the amount of EMs for drivers and pedestrians is shown in **Fig. 2.5** [2, 7, 66]. The SD for the vertical and horizontal directions can be found in each study, assuming a 2D Gaussian distribution. In the rural driving sequence, the eye movement range is minimum [7]. The extent is slightly wider for drivers on residential streets and major roads than it is on rural roads [30]. In particular, the residential street's horizontal SD is almost 1.8 times wider than the rural road. The research including pedestrians exhibits the broadest spread of EM. Compared to drivers, pedestrians have a far larger field of vision [66, 67].

Extent of the eye movement in existing studies				SD when assuming 2D gaussian distribution (deg.)	
				σ_{ψ}	σ_{θ}
Cengiz <i>et al.</i> (Drivers on rural road)	Range of 50 % contour (deg.)				
	Conditions	Vertical	Horizontal		
	Lit	2.9	3.6	1.1	1.2
	Unlit	3.3	3.3	1.2	1.2
Winter and Völker ¹ (Drivers)	Range most ¹ of fixations are located within (deg.)				
	Conditions	Vertical	Horizontal		
	Main road	10	10	1.6	1.6
	Residential street	10	20	1.5	2.2
Foulsham <i>et al.</i> (Pedestrians)	SD of gaze frequency distributions (deg.)				
	Vertical	Horizontal			
	5.2	7.6	5.2	7.6	

Fig. 2.5: Extent of the eye movements in existing studies

- **Eye Movement**

The area of measurement (AOM) defines the application area to be illuminated and to be considered. In case of road lighting the AOM is the road surfaces. From the perspective of the driver, the road surface

is typically perceived as a trapezoidal region. Here with respect to the object coordinate system (θ', ϕ') , AOM is represented as a 2D function $f_{AOM}(\theta', \phi')$, in the simulation process. The value of this function is one inside the AOM and outside the AOM, it is zero.

2.5.2 Adaptation luminance simulation

Real outdoor lighting scenes typically have complex luminance distributions (LDs), making it challenging to determine an adaptation luminance. On the other hand, the laboratory tests for the mesopic photometry system were essentially carried out with uniform LDs. In addition to unevenly lighted road surfaces, the LDs for real-world lighting scenarios also include the dark sky and high-luminance sources like luminaires. All the four factors i.e. eye movements (EMs), surrounding luminance effect (SLE) on the visual system of observers, luminance distributions (LDs) and ‘area of measurement’ (AOM) affecting the adaptation luminance have been discussed in the previous section [42, 43]. The step of computation of adaptation luminance based on luminance distribution are shown below [2]:

- Calculation of Effective Luminance Distribution
- Calculation of Adaptation Luminance Distribution
- Calculation of AOM hit probability distribution
- Calculation of Adaptation luminance
- **Calculation of Effective Luminance Distribution**

Effective luminance considers the luminance from the main source as well as the surrounding source. In the absence of any surrounding source, the retinal point would adjust to a nominal luminance from every direction. SLE is defined as the small scattering of light in

all directions to a region surrounding the corresponding point in the retinal coordinate system. Consequently, the light from all directions causes SLEs that overlap and slightly obscure the projected LD.

The luminance distribution at the retinal coordinate system, $L(\theta, \phi)$ can be derived from $L(\theta', \phi')$ by replacing as $(\theta, \phi) = (\theta', \phi')$. Therefore the effective luminance distribution, $L_{effective}(\theta, \phi)$ can be computed by convolution of the projected LD and the SLE as shown in **Eq.2.28** below.

$$L_{effective}(\theta, \phi) = (L * f_{SLE})(\theta, \phi) \quad (2.28)$$

• Calculation of Adaptation Luminance Distribution

The movement of the eye of the observer is denoted by the eye movement function and therefore the effective luminance distribution is the same as the adaptation luminance distribution when the line of sight is fixed. The average of the effective luminance for the two points is what is referred to as the adaptation luminance when a point in the retinal coordinate system looks at two spots with a 50–50 probability because of the EM. Using this idea as a generalization, the EM weighted average effective brightness is adapted to each point in the retinal coordinate system. This process can be expressed by **Eq.2.29** below.

$$L_a(\theta, \phi) = (L_{effective} * f_{EM})(\theta, \phi) \quad (2.29)$$

where:

$L_a(\theta, \phi)$ is the adaptation luminance distribution,
 $f_{EM}(\theta, \phi)$ can be computed from $f_{EM}(\theta', \phi')$

by replacing (θ, ϕ) as (θ', ϕ') .

- **Calculation of AOM hit probability distribution**

Depending on the eye movement, the points on the retinal coordinate system have a distinct probability of looking inside the AOM. For example, a pedestrian's lower regions of the retinal coordinate system are likely to be more focused on a street surface (AOM) than their top regions. **Eq.2.30** can be used to determine the probability of any test point on the retinal coordinate system inside AOM, $P_{AOM}(\theta, \phi)$.

$$P_{AOM}(\theta, \phi) = (f_{AOM} * f_{EM})(\theta, \phi) \quad (2.30)$$

- **Calculation of Adaptation luminance**

Finally, the adaptation luminance of the AOM, which is the average adaptation luminance weighted with the AOM hit probability distribution, is derived using **Eq.2.31** below.

$$L_{a,AOM} = \frac{\iint L_a(\theta, \phi) P_{AOM}(\theta, \phi) d\theta d\phi}{\iint P_{AOM}(\theta, \phi) d\theta d\phi} \quad (2.31)$$

where:

L_{AOM} is the adaptation luminance of AOM.

Again, the effective adaptation luminance (L_a) can be predicted by the equation **Eq.2.32** [68] as shown below:

$$L_a = L_{local} + L_{veil} \quad (2.32)$$

where:

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

L_{veil} is the veiling luminance caused by surrounding luminance distribution.

The veiling luminance can be determined from various equations as shown below. According to the Stiles–Holladay formula [62, 64, 69–71], veiling luminance can be computed using **Eq.2.33** as shown below:

$$L_{veil} = \frac{10}{\theta^2} E_{v,vertical} \quad (2.33)$$

where:

$E_{v,vertical}$ is the vertical illuminance at the observer’s eye due to surrounding source,

θ is the angle between the surrounding source and the line of sight.

Considering several factors for ex. observer’s age, eye pigment, and data for ranges of angle near the fovea, the CIE has defined a general disability glare equation [72–74] as shown below in **Eq.2.34**.

$$L_{veil} = \left\{ \frac{10}{\theta^3} + \left[\frac{5}{\theta^2} + \frac{0.1p}{\theta} \right] \cdot \left[1 + \left(\frac{A}{62.5} \right)^4 \right] + 0.0025p \right\} E_{v,vertical} \quad (2.34)$$

where:

A is the observer’s age in years,

p is the eye pigment factor (the value is 0 for black eyes to 1.2 for very light-blue eyes).

According to Fry equation [75], veiling luminance can be computed using **Eq.2.35** as shown below:

$$L_{veil} = 9.2 \sum \frac{E_{v,n}}{\theta(\theta + 1.5)} \quad (2.35)$$

where:

$E_{v,n}$ is the normal illuminance on a plane perpendicular to the

lamp direction at the observer's eye due to a glare source, θ is angle (in degrees) between the surrounding source and a task point where the veiling luminance is caused.

According to Uchida & Ohno model [17], veiling luminance can be computed using **Eq.2.21** as shown previously. Three veiling luminance models i.e. are: Uchida and Ohno model **Eq.2.21**, CIE general disability glare model **Eq.2.34** and Fry model **Eq.2.35** are used for computation in this work.

2.6 Measurement Methods for mesopic adaptation luminance

Since S/P luminance meters are not widely available commercially, two measurement methods for mesopic photometry system are available to take care the error caused by spectral reflectance of road surfaces [29, 68]:

- Adaptation Spectral Power Distribution method
- Source Spectral Power Distribution method
- **Adaptation Spectral Power Distribution method**

In this method, the SPD of all the test points has the same SPD as the adaptation field. This SPD method can evaluate the mesopic quantities without S/P luminance meters. The mesopic luminance of any test point can be computed by **Eq.2.36**. The scotopic luminance can be calculated from the corresponding photopic luminance and S/P ratio of the adaptation field ($R_{SP,a}$). The mesopic luminance of the test points can be derived from the equation **Eq.2.38**.

$$L_{mes;m,t} \simeq \bar{L}_{mes;m,t} = \frac{mL_{v,t} + (1 - m)L_{v,t}R_{SP,a}V'(\lambda_a)}{m + (1 - m)V'(\lambda_a)} \quad (2.36)$$

The mesopic enhancement factor $(F_{mes})(L_{v,a}; R_{SP,a})$ is the ratio of mesopic luminance to the photopic adaptation luminance as shown in **Eq.2.37**.

$$F_{mes}(L_{v,a}; R_{SP,a}) = \frac{L_{mes;m,a}}{L_{v,a}} = \frac{m + (1 - m)R_{SP,a}V'(\lambda_a)}{m + (1 - m)V'(\lambda_a)} \quad (2.37)$$

Therefore,

$$\bar{L}_{mes;m,t} = F_{mes}(L_{v,a}; R_{SP,a}) L_{v,t} \quad (2.38)$$

This approach may contain some inaccuracy when the SPDs differ since it expects that the relative SPD of each test point is the same as the adaption field. These discrepancies may be caused by the following: variations in the installed lighting's SPD in different directions, non-uniformity of spectral reflectance among field test points, and the presence of alternative light source types with SPDs that differ from the installed lighting [54]. To measure the adaption luminance, a S/P luminance metre is still required. The scotopic detector's S/P ratio, however, may be greater than the S/P luminance meter's, which is used to determine the test points. This is so that the S/P luminance metre can measure the adaptation luminance with a bigger FOV and more incoming light because the adaptation field has a larger FOV than the test points.

- **Source Spectral Power Distribution method**

In this method, the SPD of the adaptation field and the test point are same as the SPD of the light source [66]. In this method, the scotopic adaptation luminance $L'_{v,a}$ can be calculated from the corresponding photopic adaptation luminance $L_{v,a}$ and S/P ratio of the lamp ($R_{SP,a}$) using **Eq.2.39**.

$$L'_{v,a} \simeq R_{SP,a}L_{v,a} \quad (2.39)$$

Though the light that reaches viewers' eyes is typically reflected from field objects or the road surface, this method ignores the spectral reflectance of the items that are reflecting the light. This approach may therefore result in some error when the spectral reflectance is not neutral. Because of the non-uniformity of the SPDs in the adaptation field, this method may also result in the same kind of inaccuracy as the adaptation SPD method. If the source SPD is known, this method's distinctive feature is that S/P luminance metres are no longer required. Conventional luminance metres, whose spectral responsiveness matches $V(\lambda)$, can be used to detect light levels in the field, just like present methods.

- **Determination of adaptation coefficient and mesopic luminance**

According to CIE TN 007:2017 the mesopic luminance can be calculated by the following steps [58, 59] :

- * Calculation of of the photopic adaptation luminance, $L_{v,adapt}$ which is the average of all the point specific photopic luminance of the adaptation field.
- * Calculation of the scotopic adaptation luminance, $L'_{v,adapt}$, by multiplying $L_{v,adapt}$ by and S/P ratio of light source i.e. R_{SP} .
- * Computation of the mesopic adaptation luminance, $L_{mes,adapt}$, and the adaptation coefficient, m , from the corresponding photopic/scotopic adaptation luminances as defined in CIE 191:2010 or from look-up tables of the CIE 191:2010 [3].
- * Calculation of the mesopic enhancement factor $F_{mes}(L_{v,adapt};R_{SP})$, from the corresponding mesopic adaptation luminance and the photopic adaptation luminance.

- * Conversion of the photopic luminance at each point of the application area to the mesopic luminance by multiplying the photopic luminance of the point by the mesopic enhancement factor [76].

3 Computation of Adaptation luminance

In this chapter different outdoor lighting conditions are simulated using several light sources that are commonly utilized in outdoor lighting applications. The effect of surrounding light sources on the application area in a real-world scenario is also achieved by taking into account surrounding light sources (SLSs). The determination of the adaptation luminance has been predicated on the observer's peripheral adaptation condition. The simulation of outdoor lighting conditions allows for a more accurate representation of how different light sources affect the application area. By considering surrounding effects, the simulation can provide a realistic depiction of how these sources impact the overall lighting environment.

3.1 Introduction

The present photometry system involved in lighting design, experimentation and research work is based on the photopic luminous efficiency function. Although many outdoor lighting application areas are subjected to mesopic vision, there is still no international method and guideline on the implementation of mesopic photometry system in real outdoor lighting applications. The absence of meters and methods for the determination of mesopic and adaptation luminance for real-lit areas are another challenge for the designers. Unlike the mesopic luminance, determination of the adaptation luminance must consider the adaptation field and adaptation state of the observer [17].

In this chapter, outdoor lighting conditions have been simulated with different light sources that are mostly used in outdoor lighting applications. Four different types of lamps that are commonly used in outdoor lighting applications i.e. High-Pressure Sodium Vapour (HPSV), Metal Halide (MH), White LED (WLED), Cool White LED (CWLED) have been considered as the main light source (MLS). Three surrounding light sources (SLSs) are also taken into consideration to achieve the effect of surrounding light sources on the application area in a real scenario. Again these surrounding lighting effects (SLE) have been created for two different conditions i.e. warm white SLS (WWSLS) & cool white SLS (CWSLS). Each condition is achieved by three fluorescent lamps as SLSs of the same luminous intensity distribution pattern. Therefore for each MLS two different surrounding ambience is available, one is with CWSLS, and the another one is for WWSLS,

3.2 Computational Methods

The area under consideration for the simulation set-up has been shown in **Fig.3.1**. This area has been simulated in MATLAB software with

one MLS and three SLSs. Later the same work was done in the laboratory environment. One similar set-up has been developed in the laboratory and the work has been validated. The mounting height of the luminaire is considered as 3.6m as this height was taken in the laboratory experiment also. The total application area is divided into 11x6 i.e.66 grid points with a spacing of 0.5 meters on each side. Point-specific photopic luminance values are computed from the luminous intensity distribution profile of the luminaires for an observer located at a distance of 6 meters from the nadir point. The mounting height of the surrounding light sources is 2.5 meters [77]. The major steps involved in the calculation of mesopic and adaptation luminance are as follows:

- Computation of photopic luminance,
- Computation of corresponding mesopic luminance and
- Computation of corresponding adaptation luminance.

The above steps have been repeated for different combinations of main light sources and surrounding light sources. Point specific mesopic luminance values for all the grid points are calculated from corresponding photopic luminance using CIE table [3]. The computation of mesopic luminance is carried out using S/P ratio of MLS. On the other hand, effects of veiling luminance due to SLSs are considered to find out the value of adaptation coefficient (m).

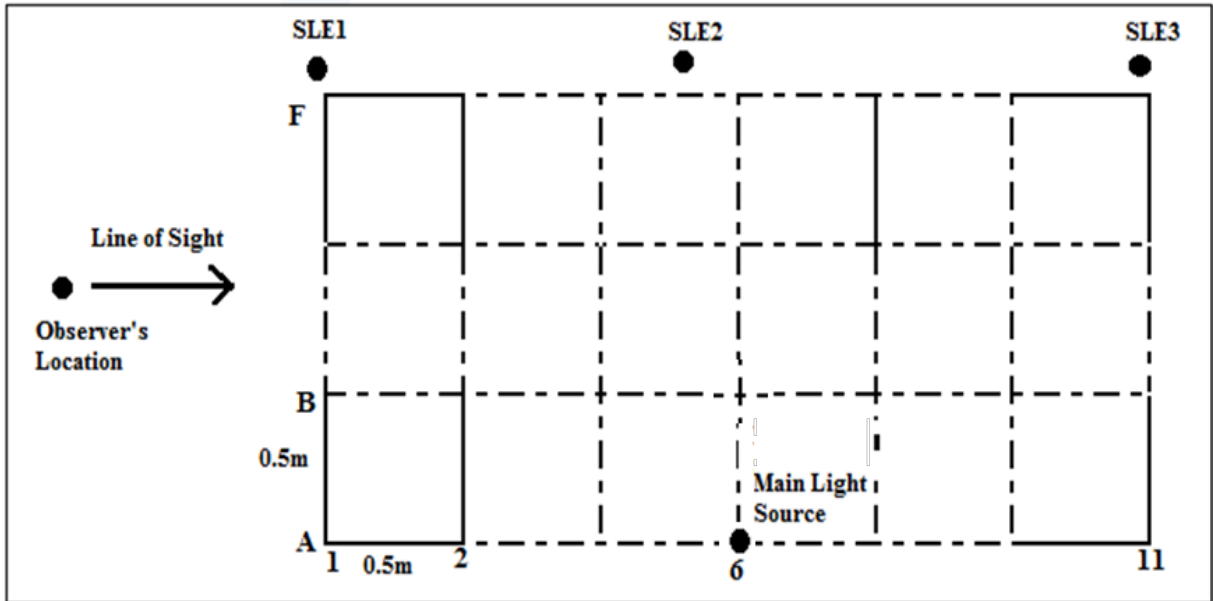


Fig. 3.1: Layout of Grid

3.2.1 Computation of Photopic Luminance

The computation method for point-specific photopic luminance (L_p) for the entire AOM is discussed below. The method considers factors such as the reflectance properties of surfaces, the light sources, mounting height and the distance between the observer and the points being analyzed.

- **Computational Flow Diagram**

The point specific photopic luminance i.e. luminance of each grid point has been computed by a computational flow diagram as shown in **Fig.3.2**, details of which has been explained below. The luminous intensity distribution of the luminaires used in the simulation has been measured by high precision rotation luminaire type Goniophotometer of model LSG 1700B [78] and then the same lamp-luminaire setup has been used in the computation process. Luminous intensity values are interpolated from this intensity distribution table for all grid points.

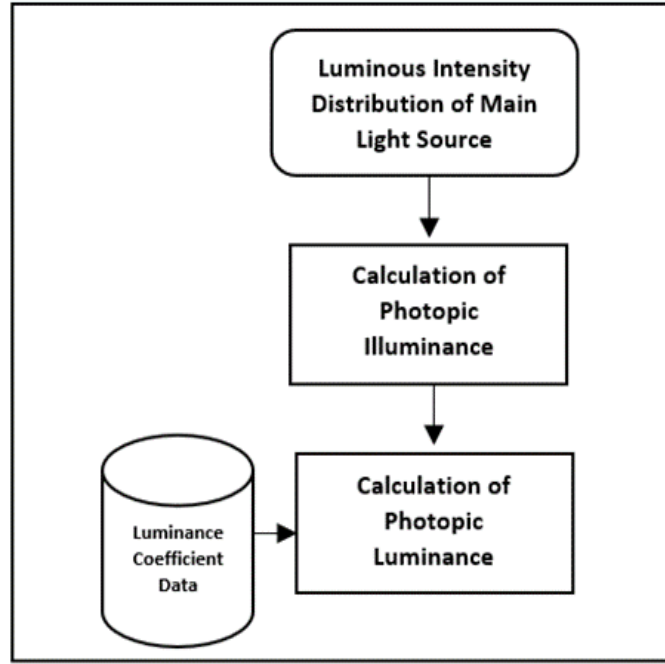


Fig. 3.2: Flow chart for computation of photopic luminance

Point specific illuminance (E_p) of all grid points has been calculated using **Eq.3.1** as shown below.

$$E_p = \frac{I_p(C, \gamma)}{h^2} \cos^3 \gamma \quad (3.1)$$

where:

$I_p (C, \gamma)$ is luminous intensity in the direction defined by the horizontal and vertical angles C and γ ,

h is luminaire mounting height

The photopic luminance of each grid point then can be determined using equation **Eq.3.2**. The luminance coefficient of the measurement surface has been computed to calculate photopic luminance from the corresponding illuminance value.

$$L_p = q(\beta, \gamma) E_p = \frac{I_p(C, \gamma)}{h^2} r(\beta, \gamma) \quad (3.2)$$

where:

$\mathbf{q}(\beta, \gamma)$ is luminaire coefficient of the surface for the angle (γ) of light incidence concerned and angle(β) between vertical plane of observation and plane of light incidence,

$\mathbf{r}(\beta, \gamma)$ is reduced luminance coefficient ($\cos^3 \gamma$) of the road surface for the angle (γ) of light incidence concerned and for the angle (β) between vertical plane of observation and vertical plane of light incidence.

The necessary MATLAB software codes for this computation are provided in Annexure-I.

• Results and Analysis

All the calculated data are shown below using CWLED as MLS. The point specific photopic illuminance values of the area are computed from the luminous intensity distribution of the CWLED following the method described above using **Eq.3.1** is shown in **Table 3.1**.

Table 3.1: Calculated Photopic Illuminance (in lux) for 66 grid points

	A	B	C	D	E	F
1	58.1	69.2	66.7	62.3	56.4	49.4
2	64.0	77.3	74.8	69.8	63.2	54.8
3	69.6	85.1	82.5	77.1	69.3	59.9
4	74.2	91.7	89.1	83.4	74.8	64.3
5	77.3	96.1	93.7	87.6	78.4	67.2
6	78.4	97.7	95.3	89.1	79.8	68.2
7	77.3	96.1	93.7	87.6	78.4	67.2
8	74.2	91.7	89.1	83.4	74.7	64.3
9	69.6	85.1	82.5	77.1	69.3	59.9
10	64.1	77.3	74.8	69.9	63.0	54.8
11	58.1	69.2	66.7	62.3	56.4	49.4

In absence of r-values of the application surface, the corresponding luminance coefficient values are experimentally determined using measured point specific illuminance and luminance data. The computed luminance coefficient of the surface for the angle of light incidence

concerned and angle between vertical plane of observation and plane of light incidence are shown in **Table 3.2**.

Table 3.2: Computed Luminance co-efficient (q) values

	A	B	C	D	E	F
1	0.03689	0.04550	0.08461	0.04140	0.03624	0.02639
2	0.03188	0.03657	0.04337	0.03137	0.02680	0.02600
3	0.02491	0.03055	0.03295	0.02879	0.02193	0.03197
4	0.02387	0.02365	0.03245	0.02432	0.02618	0.02878
5	0.02237	0.02282	0.02345	0.02225	0.01987	0.02767
6	0.02368	0.01954	0.02194	0.02412	0.02007	0.02338
7	0.02155	0.02024	0.02121	0.01950	0.01981	0.02386
8	0.02825	0.01991	0.01894	0.01920	0.02264	0.02892
9	0.02850	0.02302	0.02264	0.02498	0.02146	0.03047
10	0.02151	0.02614	0.02578	0.02338	0.02445	0.03442
11	0.02522	0.03129	0.03221	0.03289	0.03920	0.03779

Then theoretical photopic luminance (L_p) shown in **Table 3.3** are determined by multiplying illuminance (E_p) with luminance coefficient (q) as shown in **Eq.3.2**.

Table 3.3: Calculated photopic luminance (in cd/m²)

	A	B	C	D	E	F
1	2.39	2.78	2.70	2.11	1.61	1.10
2	3.90	3.49	4.12	3.11	2.14	1.15
3	3.24	3.56	2.14	3.56	2.12	1.45
4	4.70	3.42	3.34	2.53	2.14	1.46
5	4.12	4.89	2.87	3.34	2.18	1.87
6	3.87	4.27	2.68	3.12	2.16	1.31
7	3.98	3.90	2.85	2.95	2.44	1.58
8	2.54	2.77	1.98	2.27	2.56	1.12
9	3.23	2.98	3.47	2.12	1.45	1.01
10	2.02	1.77	2.54	2.56	1.27	1.28
11	1.62	1.51	1.56	1.58	1.38	1.12

3.2.2 Computation of Mesopic luminance

The computation method for point specific mesopic luminance (L_m) for the entire AOM involves considering the spectral sensitivity of the

human eye under mesopic conditions. This is done by weighting the luminance values at different wavelengths with appropriate coefficients. Additionally, the computation method considers the spatial distribution of luminance across the AOM to accurately determine the overall mesopic luminance.

- **Computational Flow Diagram**

The mesopic luminance (L_m) of all the grid points are computed from the corresponding photopic luminance data as shown below in **Fig.3.3**. This calculation requires the S/P ratio of the MLS used in the application area. Therefore, all the mesopic luminance values are computed using the photopic luminance and the measured S/P ratio of the CWLED lamp using the CIE191-2010 table shown in **Table 3.4** [3] and the computation flow diagram is shown in **Fig.3.4**.

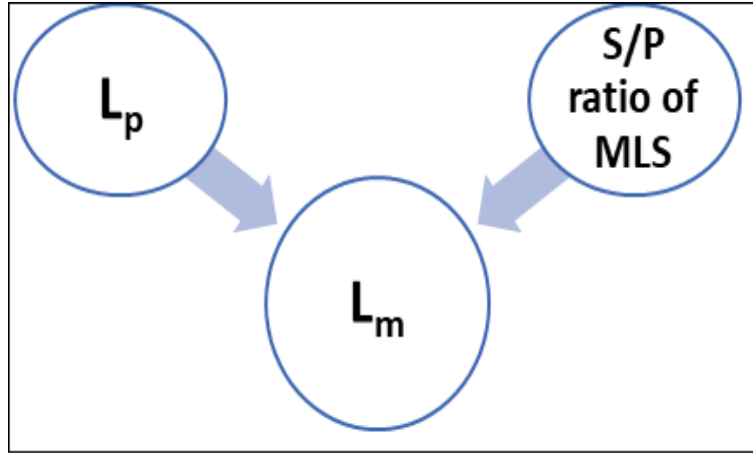


Fig. 3.3: Process for computation of mesopic luminance

Table 3.4: Values of Lmes of the recommended Mesopic system as a function of photopic luminance and S/P ratio

LPS -	S/P	Photopic Luminance cd/m ²						
		0.01	0.03	0.1	0.3	1	3	4.5
HPS ~	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
	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
	MH warm white ~	1.05	0.0104	0.0308	0.1017	0.3032	1.0054	3.0046
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
MH day light	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
	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

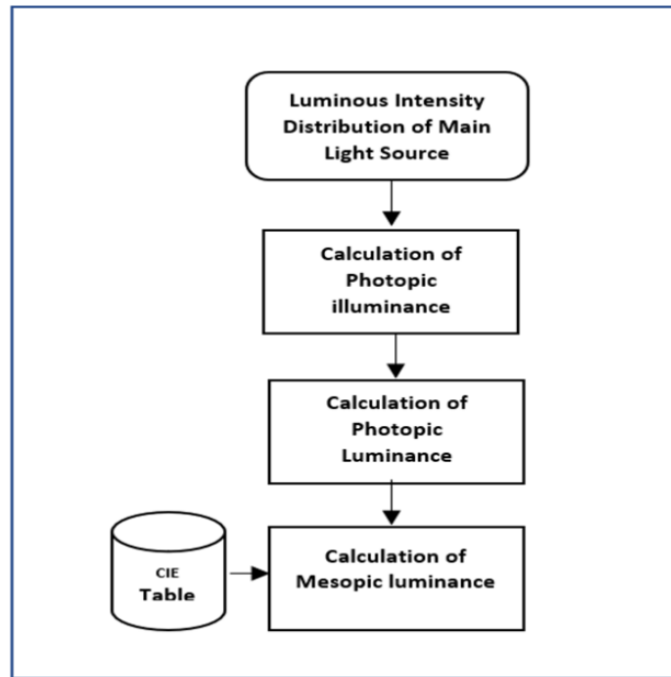


Fig. 3.4: Computational Flow Diagram for Mesopic Luminance

• **Results and Analysis**

Point specific mesopic luminance (L_m) values are calculated for CWLED as MLS from the calculated photopic luminance (L_P) data shown in **Table 3.3** and provided in **Table 3.5** below. By utilizing the data from **Table 3.3** and the codes provided in Annexure-II, accurate calculations can be made to determine the specific mesopic luminance values for each of the 66 grid points.

Table 3.5: Calculated mesopic luminance (in cd/m^2) with only CWLED

	A	B	C	D	E	F
1	2.45	2.84	2.90	2.23	1.71	1.25
2	4.29	3.61	4.34	3.30	2.30	1.41
3	3.62	3.84	2.34	3.86	2.40	1.69
4	5.00	3.60	3.46	2.73	2.43	1.68
5	4.35	5.00	2.96	3.50	2.38	2.04
6	4.12	4.47	2.98	3.20	2.46	1.51
7	4.38	4.10	3.15	3.05	2.64	1.71
8	2.74	2.97	2.12	2.47	2.74	1.28
9	3.50	3.10	3.57	2.38	1.67	1.19
10	2.18	1.97	2.74	2.89	1.47	1.41
11	1.82	1.71	1.71	1.72	1.56	1.35

The table shows the mesopic luminance of the application area due to the MLS only. But in real city roads, there are many surrounding light sources also present which illuminates the application area along with the MLS. To analyse the effect of these surrounding light sources, two different ambiences have been created using warm and cool white surrounding light sources (Fluorescent tube light i.e. FTL in this case). Hence there are two sets of computation performed in this work for two different types of Surrounding light sources (SLS):

- * **For CWSLS:** In Set1 mesopic luminance is computed when the surrounding light sources are cool white FTL.

* **For WWSLS:** In Set2 same process is repeated when surrounding light sources are warm white FTL.

* **Set 1: MLS (CWLED) and CWSLS**

Three surrounding lamps are taken into consideration as shown in **Fig.3.1** to understand the effect on the illumination due to the SLS. The mesopic luminance due to these CWFTLs is shown below in **Table 3.6**.

Table 3.6: Calculated mesopic luminance (in cd/m²) with only CWSLSs

	A	B	C	D	E	F
1	0.45	0.71	1.50	1.89	0.60	0.07
2	0.86	0.89	1.09	1.26	0.57	0.06
3	0.66	0.75	1.25	1.38	0.41	0.06
4	0.54	0.89	0.96	1.13	2.06	0.06
5	0.83	0.71	0.95	1.11	2.14	0.09
6	0.68	0.91	0.94	0.98	0.88	0.10
7	0.76	0.78	0.74	0.98	0.33	0.08
8	1.04	0.71	0.68	0.86	0.43	0.85
9	0.78	0.81	0.97	1.25	0.33	0.08
10	0.76	0.76	1.03	1.12	0.31	0.10
11	0.60	0.68	0.67	1.11	0.37	0.10

The combined effect of MLS (i.e.CWLED) and CWSLS are studied here and the mesopic luminance for all 66 points is computed. This combination of MLS and CWSLS is referred to as Set 1 and shown in **Table 3.7**.

* **Set 2: MLS (CWLED) and WWSLS**

Here the surrounding lighting effect is created using warm white FTL. The mesopic luminance due to these WWSLS are shown below in **Table 3.8**.

Mesopic luminance for all 66 points is computed again when the area is illuminated by the MLS (i.e. CWLED) and WWSLS. This combination is referred to as Set 2 and shown in **Table 3.9**.

Table 3.7: Calculated mesopic luminance (in cd/m^2) for CWLED as MLS with all CWSLS

	A	B	C	D	E	F
1	2.99	5.00	5.00	2.94	1.25	1.05
2	4.22	5.00	5.00	3.51	2.25	1.63
3	4.40	5.00	4.24	4.23	2.87	2.16
4	4.70	4.39	5.00	3.77	2.79	1.48
5	5.00	3.89	4.50	3.57	3.41	1.95
6	4.37	4.38	3.69	3.52	2.81	2.12
7	3.79	3.45	4.30	3.09	3.11	1.76
8	3.75	3.11	3.05	2.46	2.28	1.29
9	2.67	2.53	3.41	3.01	1.74	1.43
10	2.42	2.25	2.51	2.19	1.64	1.32
11	1.81	2.04	1.54	2.23	1.89	1.18

Table 3.8: Calculated mesopic luminance (in cd/m^2) with only SLSs

	A	B	C	D	E	F
1	0.69	0.65	0.77	0.79	0.88	0.35
2	0.76	0.66	0.79	0.82	0.89	0.34
3	0.74	0.70	0.78	0.83	0.90	0.37
4	0.68	0.71	0.78	0.80	0.84	0.37
5	0.73	0.72	0.76	0.78	0.86	0.40
6	0.70	0.76	0.74	0.78	0.75	0.36
7	0.73	0.74	0.75	0.79	0.68	0.44
8	0.76	0.72	0.74	0.78	0.68	0.41
9	0.77	0.75	0.80	0.80	0.68	0.43
10	0.69	0.74	0.80	0.87	0.66	0.44
11	0.71	0.76	0.70	0.79	0.67	0.44

3.2.3 Computation of Adaptation luminance

As discussed in the previous section **2.10**, the adaptation luminance (L_a) method depends on four factors i.e. luminance distribution (LD), eye movement (EM), surrounding luminance effect (SLE) and area of measurement (AOM). Standard deviation (SD) for horizontal and vertical directions of eye movement is considered as 5.2 and 7.6 deg respectively from the previous study of EM distribution for pedestrians [6]. As the line of sight is not fixed for any pedestrian, it has comparatively a wider range of eye movement, opposite to a drive with very

Table 3.9: Calculated mesopic luminance (in cd/m²) for CWLED and all WWSLSs

	A	B	C	D	E	F
1	2.18	2.73	5.00	3.89	2.10	1.35
2	5.00	3.99	3.67	5.00	1.86	1.40
3	4.15	3.93	4.15	3.29	3.21	1.65
4	5.00	4.15	4.34	4.23	3.78	1.42
5	5.00	5.00	3.68	3.66	4.12	2.07
6	4.50	4.31	3.71	4.05	3.51	1.66
7	5.00	5.00	4.37	5.00	3.17	1.93
8	4.24	3.32	3.68	3.52	3.10	1.17
9	4.27	3.53	4.48	4.28	2.35	1.48
10	2.22	2.67	3.98	3.80	1.95	1.57
11	2.36	2.39	2.27	2.61	2.33	1.44

limited eye movement and a fixed line of sight. Area of measurement (AOM) function $P_{AOM}(\theta, \phi)$ is considered as 1.

The adaptation luminance (L_a) of the measurement area is defined by the average adaptation luminance weighted with the AOM hit probability distribution and can be estimated using **Eq.3.3** below. [19].

$$L_a = \frac{\iint L_a(\theta, \phi) P_{AOM}(\theta, \phi) d\theta d\phi}{\iint P_{AOM}(\theta, \phi) d\theta d\phi} \quad (3.3)$$

where:

$L_a(\theta, \phi)$ is the adaptation LD (cd) and it is comprised of the effects due to surrounding luminance effect (SLE), luminance distribution (LD) and eye movement (EM),

$P_{AOM}(\theta, \phi)$ is the probability for each point on retinal coordinate system to look inside area of measurement,

θ, ϕ are horizontal and vertical angle of any object within field of view corresponding to the position of the observer.

Adaptation luminance has been simulated using the computed luminance distribution (LD) and surrounding luminance effect (SLE). Both the mesopic luminance and adaptation luminance are compared to un-

derstand the applicability of CIE model in outdoor lighting. Veiling Luminance caused by the surrounding light sources has an impact on the adaptation luminance perceived by the observer. To calculate the surrounding luminance effect three veiling luminance models were used in this study as discussed below [39]. The veiling luminance model given by Uchida and Ohno [17] in **Eq.3.4** below :

$$L_{veil} = \frac{260}{\theta^3} E_v \quad (3.4)$$

The veiling luminance model provided by Fry [75] in **Eq.3.5** below:

$$L_{veil} = 9.2 \sum \frac{E_{gl}}{\theta(\theta + 1.5)} \quad (3.5)$$

The veiling luminance model provided by CIE general disability glare method [72] in **Eq.3.6** below:

$$L_{veil} = \left\{ \frac{10}{\theta^3} + \left[\frac{5}{\theta^2} + \frac{0.1p}{\theta} \right] \cdot \left[1 + \left(\frac{A}{62.5} \right)^4 \right] + 0.0025p \right\} E_{gl} \quad (3.6)$$

where:

$L_{veiling}$ is the veiling luminance caused by a high-luminance light source,

θ is the angle in degree between the line of fixation and the high-luminance source,

A(43 years) is the observer's age in years,

p(0.9) is the eye pigment factor, E_v is the illuminance on a plane perpendicular to a straight line between the observer's eye and the working plane,

E_{gl} is the illuminance on a vertical plane at the observer's eye. Consequently, E_{gl} is E_v multiplied by the cosine of θ .

- **Computational Flow Diagram**

As adaptation luminance depends on the luminance of the application are i.e. local luminance and the veiling luminance, it has been computed using **Eq.3.7**.

$$L_a = L_{local} + L_{veil} \quad (3.7)$$

Again the veiling luminance depends on visual angles and vertical illuminance as shown in **Fig.3.5**. The computational flow diagram has been shown in **Fig.3.6**. The visual angles between the source and task points (here grid points) in degrees are calculated using MATLAB software. Veiling Luminance is calculated using **Eq.3.4**, **Eq.3.5** and **Eq.3.6**. Local luminance (L_{local}) values (here photopic luminance values on the grid points) are computed previously. The values of Local Luminance and Veiling Luminance of each grid points are added to get Adaptation Luminance (L_a).

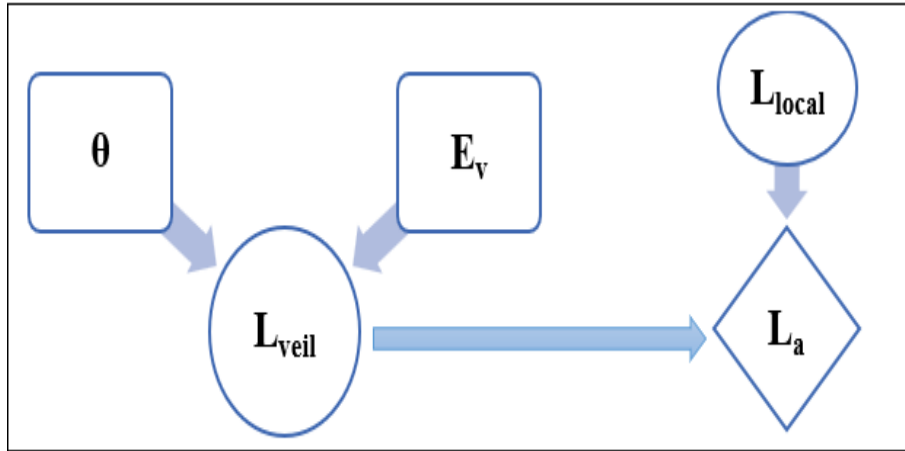


Fig. 3.5: Process for computation of adaptation luminance

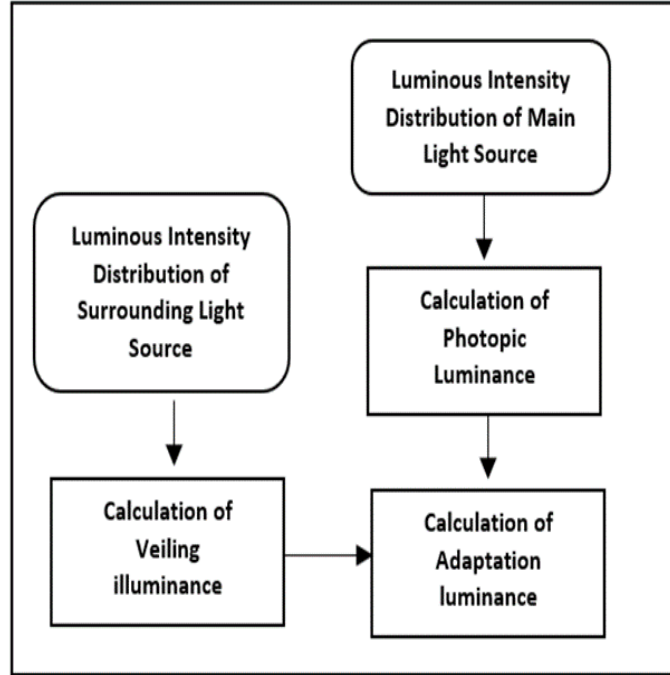


Fig. 3.6: Computational Flow Diagram for Adaptation Luminance

• Results and Analysis

The simulation of adaptation luminance (L_a) involves two Sets as discussed above. Three adaptation luminance values i.e. (L_{a1}), (L_{a2}), (L_{a3}) are simulated from three veiling luminance models i.e. Uchida and Ohno model, Fry model, CIE general disability glare equation model respectively. These veiling luminance values are then used as inputs to simulate the adaptation luminance (L_a) using MATLAB software. The simulation process allows for the comparison and analysis of the different veiling luminance models in predicting adaptation luminance values.

* Set 1: MLS (CWLED) and CWSLS

Point specific adaptation luminance (L_a) values are calculated for 66 grid points from the measured photopic luminance (L_p) data while CWLED has been used as main light source and CWFTL has been used as SLS. Adaptation luminance (L_{a1} , L_{a2} , L_{a3}) for all the grid points

(in cd/m^2) is listed below in **Table 3.10**, **Table 3.11** and **Table 3.12** respectively.

Table 3.10: Adaptation Luminance (L_{a1}) (in cd/m^2) from Uchida and Ohno model

	A	B	C	D	E	F
1	2.41	2.87	3.04	2.58	2.30	1.66
2	4.32	3.70	4.58	3.73	3.03	1.94
3	3.62	3.94	2.49	4.24	2.92	1.99
4	4.78	3.66	3.60	2.97	2.62	1.76
5	4.39	5.19	3.04	3.64	2.47	1.99
6	4.14	4.52	3.00	3.25	2.47	1.44
7	4.39	4.11	3.15	3.04	2.60	1.63
8	2.68	2.92	2.08	2.42	2.68	1.18
9	3.46	3.05	3.54	2.32	1.59	1.10
10	2.10	1.90	2.67	2.82	1.38	1.32
11	1.74	1.62	1.62	1.63	1.45	1.26

Table 3.11: Adaptation Luminance (L_{a2})(in cd/m^2) from Fry model

	A	B	C	D	E	F
1	2.43	2.89	3.05	2.55	2.19	1.55
2	4.34	3.71	4.57	3.66	2.84	1.75
3	3.63	3.94	2.46	4.15	2.74	1.85
4	4.79	3.65	3.56	2.88	2.52	1.68
5	4.39	5.17	3.00	3.57	2.40	1.97
6	4.14	4.51	2.97	3.20	2.42	1.42
7	4.39	4.10	3.12	3.01	2.57	1.61
8	2.68	2.91	2.06	2.40	2.66	1.17
9	3.45	3.04	3.52	2.30	1.57	1.09
10	2.10	1.89	2.66	2.81	1.37	1.31
11	1.73	1.61	1.61	1.62	1.45	1.25

*** Set 2: MLS (CWLED) and WWSLS**

Point specific adaptation luminance (L_a) values are calculated again for 66 grid points from the measured photopic luminance (L_p) data while CWLED has been used as main light source and WWFTL has been used as SLS. Adaptation luminance (L_{a1}, L_{a2}, L_{a3}) for all the grid

Table 3.12: Adaptation Luminance (L_{a3})(in cd/m^2) from CIE general disability glare equation model

	A	B	C	D	E	F
1	2.47	2.96	3.14	2.68	2.33	1.63
2	4.38	3.77	4.65	3.76	2.96	1.82
3	3.67	3.99	2.52	4.22	2.81	1.88
4	4.82	3.69	3.60	2.92	2.54	1.69
5	4.41	5.20	3.03	3.59	2.41	1.97
6	4.16	4.53	2.98	3.22	2.43	1.42
7	4.40	4.11	3.13	3.02	2.58	1.61
8	2.68	2.92	2.07	2.41	2.66	1.17
9	3.46	3.05	3.53	2.31	1.57	1.09
10	2.10	1.89	2.66	2.81	1.37	1.31
11	1.74	1.62	1.62	1.62	1.45	1.25

points (in cd/m^2) is listed below in **Table 3.13**, **Table 3.14** and **Table 3.15** respectively. The calculated adaptation luminance values provide valuable information about the perceived brightness at each point. These values can be used to assess the overall lighting conditions and comparing the adaptation luminance for different light sources can help evaluate their effectiveness in providing adequate illumination.

Table 3.13: Adaptation Luminance (L_{a1}) (in cd/m^2) from Uchida and Ohno model for WWSLS

	A	B	C	D	E	F
1	2.35	2.75	2.80	2.13	1.60	1.14
2	4.26	3.54	4.30	3.21	2.20	1.30
3	3.56	3.79	2.25	3.81	2.30	1.58
4	4.72	3.55	3.39	2.64	2.33	1.57
5	4.34	5.10	2.89	3.43	2.28	1.95
6	4.12	4.49	2.94	3.15	2.37	1.41
7	4.40	4.12	3.15	3.02	2.57	1.61
8	2.72	2.97	2.16	2.49	2.73	1.18
9	3.54	3.17	3.74	2.40	1.76	1.09
10	2.26	2.14	2.98	3.18	1.78	1.31
11	1.97	2.03	2.31	2.59	2.47	1.25

Table 3.14: Adaptation Luminance (L_{a2})(in cd/m^2) from Fry model for WWSLS

	A	B	C	D	E	F
1	2.36	2.75	2.80	2.13	1.60	1.14
2	4.26	3.55	4.30	3.21	2.20	1.30
3	3.56	3.79	2.25	3.80	2.30	1.58
4	4.72	3.55	3.39	2.64	2.33	1.57
5	4.34	5.09	2.88	3.43	2.28	1.94
6	4.12	4.48	2.92	3.14	2.37	1.40
7	4.39	4.10	3.12	2.99	2.55	1.60
8	2.71	2.95	2.11	2.44	2.69	1.17
9	3.52	3.13	3.66	2.35	1.66	1.08
10	2.23	2.07	2.85	3.01	1.57	1.30
11	1.91	1.90	2.04	2.14	1.94	1.24

Table 3.15: Adaptation Luminance (L_{a3})(in cd/m^2) from CIE general disability glare equation model for WWSLS

	A	B	C	D	E	F
1	2.36	2.75	2.80	2.13	1.60	1.14
2	4.26	3.55	4.30	3.21	2.20	1.30
3	3.57	3.80	2.25	3.81	2.30	1.58
4	4.72	3.55	3.39	2.64	2.33	1.57
5	4.34	5.10	2.89	3.43	2.28	1.94
6	4.13	4.49	2.93	3.14	2.37	1.40
7	4.41	4.12	3.13	3.00	2.56	1.60
8	2.73	2.96	2.13	2.45	2.69	1.17
9	3.55	3.15	3.68	2.36	1.67	1.08
10	2.26	2.10	2.88	3.03	1.58	1.30
11	1.95	1.95	2.09	2.19	1.98	1.24

3.3 Comparative Analysis

In this chapter one application area has been simulated and corresponding photopic, mesopic and adaptation luminance have been simulated from the luminous intensity distribution of the luminaires. The comparison among these luminance values is shown in this section to analyse the effect of spectrum of the surrounding lighting on the illuminated space.

- **Comparison of Photopic and Mesopic Luminance**

The photopic luminance of all the grid points have been evaluated from the luminous intensity distribution of the light sources and shown in **Table 3.3**. But as the illumination level falls under mesopic region, hence the mesopic values are evaluated for all the grid points considering mesopic dimensioning and CIE 191 table. These values are shown in **Table 3.5**. The distribution pattern of this photopic luminance (L_p) and mesopic luminance (L_m) are shown in **Fig.3.7**. Average values of photopic luminance (L_p) and mesopic luminance (L_m) are shown in **Fig.3.8**.

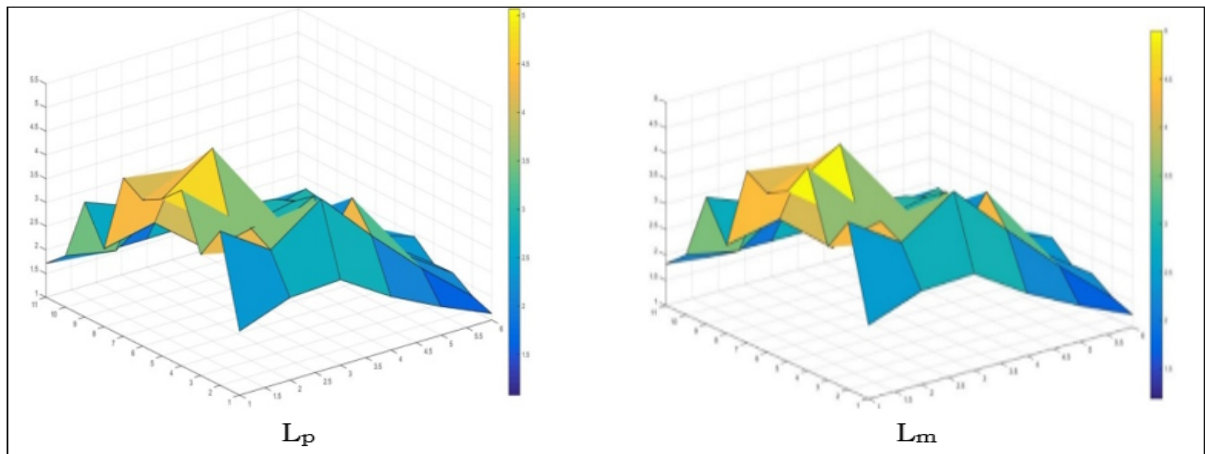


Fig. 3.7: Distribution of photopic and mesopic luminance

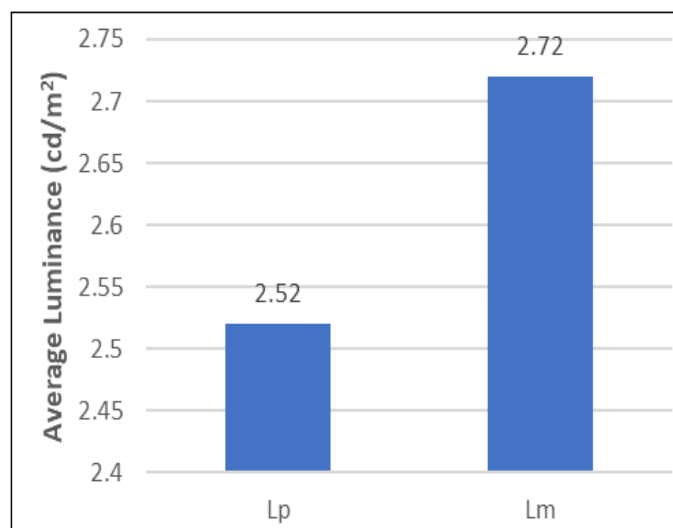


Fig. 3.8: Comparison of photopic and mesopic luminance

The average photopic and mesopic luminance are computed and shown in Fig. 3.8. Here it can be observed that the mesopic luminance is 7.9% higher than the photopic luminance as the S/P ratio of the light source (CWLED) is more than one i.e. 2.09. This indicates that the light source that emits more blue light is more effective in stimulating the mesopic visual system compared to the photopic visual system. This finding has implications for lighting design and can help optimize lighting conditions for different visual tasks.

- **Comparison of Adaptation Luminance**

- * **Set 1: MLS (CWLED) and CWSLS**

After computing photopic luminance for the entire field of measurement corresponding adaptation luminance for the said area of measurement is calculated along with the effect of cool white surrounding lighting by three methods described previously. The veiling luminance was added to the photopic luminance of the field to compute the adaptation luminance. The distribution of adaptation luminance (L_{a1}), (L_{a2}), (L_{a3}) are shown below in **Fig.3.9**. Average values of adaptation luminance from three models (L_{a1}), (L_{a2}), (L_{a3}) are shown in **Fig.3.10**. The increments to adaptation luminance from photopic luminance are 5.92%, 4.69% and 5.75% respectively. Therefore, it can be stated that calculated adaptation luminance is almost same for all the three models.

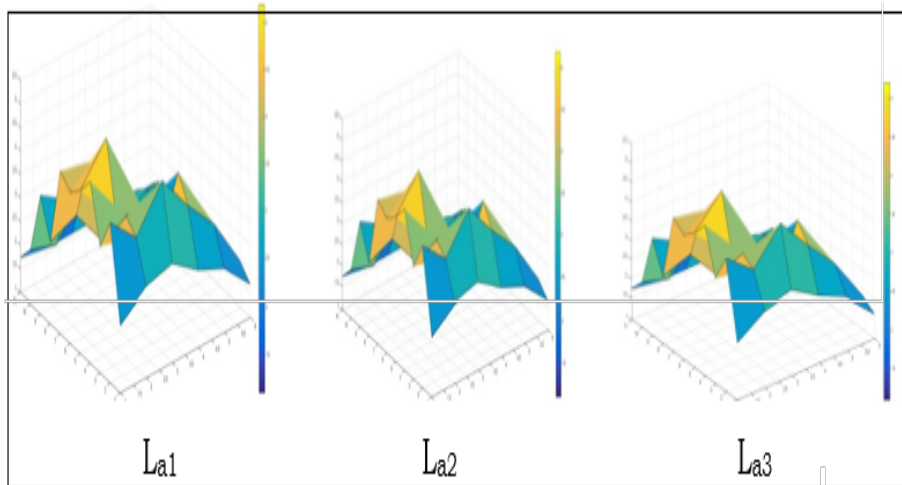


Fig. 3.9: Distribution of Adaptation luminance

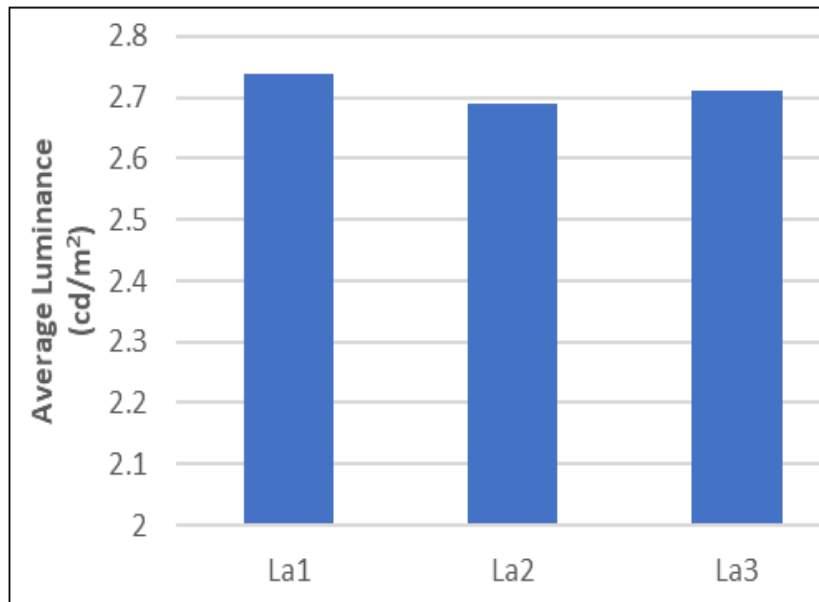


Fig. 3.10: Comparison of adaptation luminance

*** Set 2: MLS (CWLED) and WWSLS**

The adaptation luminance for the said area of measurement is calculated again along with the effect of warm white surrounding lighting by three methods described previously. The veiling luminance was added to the photopic luminance of the field to compute the adaptation luminance. The distribution of adaptation luminance (L_{a1}), (L_{a2}), (L_{a3})

are shown below in **Fig.3.11**. Average values of adaptation luminance from three models (L_{a1}), (L_{a2}), (L_{a3}) are shown in **Fig.3.12**. The increments to adaptation luminance from photopic luminance are 4.14%, 2.59%, and 2.96% respectively. Therefore, it can be stated that the calculated adaptation luminance is almost the same for all three models as shown in **Fig.3.12** for set 2 also.

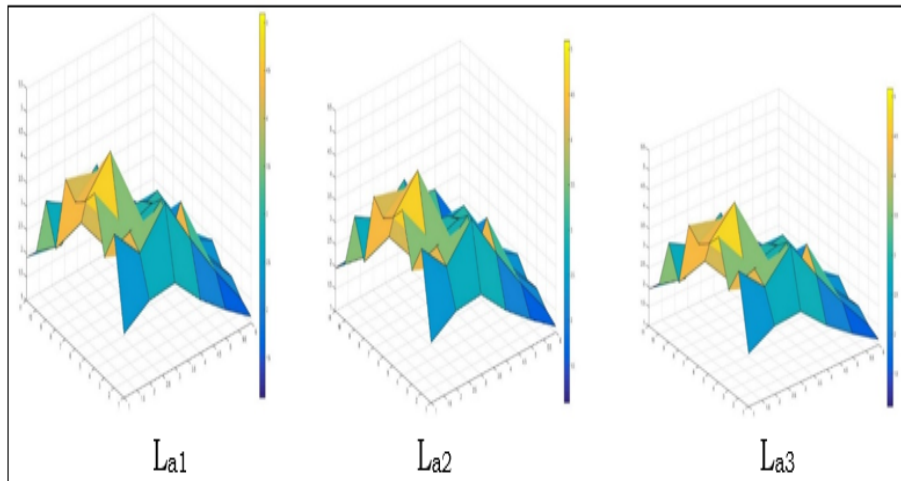


Fig. 3.11: Distribution of Adaptation luminance for WWSLS

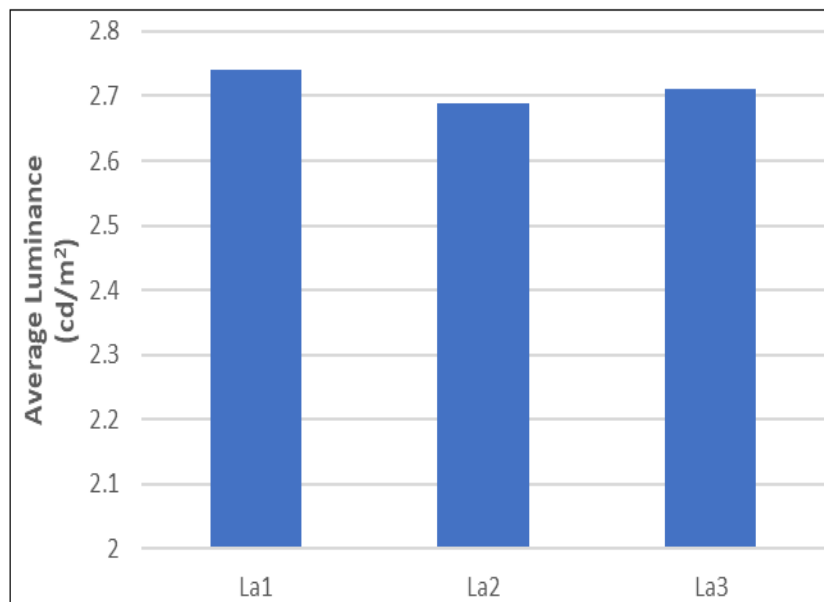


Fig. 3.12: Comparison of adaptation luminance for WWSLS

- **Comparison of Photopic, Mesopic and Adaptation Luminance**

- * **Set 1: MLS (CWLED) and CWSLS**

The photopic, mesopic and adaptation luminance values of the entire AOM are compared in this section to understand the effect of cool white surrounding lighting on the application area. Average photopic (L_p), mesopic (L_m) and adaptation luminance (L_a) due to CWLED as MLS are shown in the **Fig.3.13**. As the CIE method is followed internationally, among the three adaptation luminance shown in the previous section, the adaptation luminance calculated according to this method (i.e. L_{a3}) is considered here as L_a . Here it can be observed that in the presence of cool white SLS, the effective luminance i.e. adaptation luminance increases as the nature of spectrum of both type of sources are similar in nature.

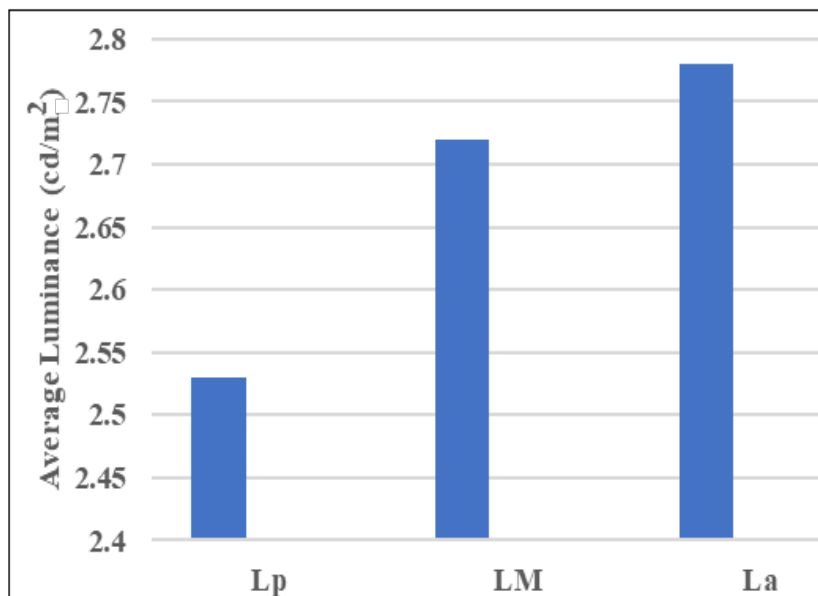


Fig. 3.13: Comparison of average luminance for Set 1

- * **Set 2: MLS (CWLED) and WWSLS**

This section compares the photopic, mesopic, and adaption luminance

values to understand how warm white ambient lighting affects the application area. **Fig.3.14** displays the average photopic (L_p), mesopic (L_m), and adaptation luminance (L_a) for CWLED as MLS. Since the CIE approach is widely used, adaptation luminance is determined using this method (i.e. L_{a3}) out of the three adaptation luminance displayed in the previous section. Here, it is evident that the effective brightness, or adaptation luminance, does not rise in the presence of warm white SLS because the sources' spectra are inherently different. This suggests that the warm white surrounding lighting does not have a significant impact on the adaptation luminance due to the cool white main light source. The opposite nature of the spectrum of the sources is causing a cancellation effect, resulting in no increase in effective luminance and hence it is less than the computed mesopic luminance in this case.

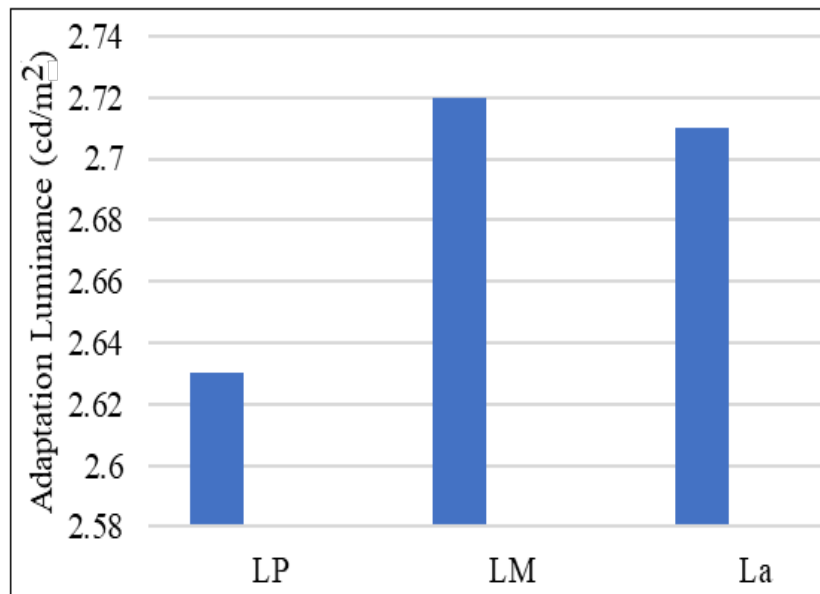


Fig. 3.14: Comparison of average luminance for Set 2

- **Effect of different types of Surrounding Source**

Comparison of average photopic, mesopic and adaptation luminance of the adaptation field for both set 1 and set 2 are shown in **Table**

3.16. From **Fig.3.15** it can be stated that the computed mesopic luminance is higher than the photopic luminance in both Set 1 and Set 2. As the S/P ratio of CWLED is 2.09, blue content is more in its spectrum. Hence the performance of this lamp is better in mesopic region. However the adaptation luminance increases in Set 1 and decreases in Set 2. As the surrounding lighting is cool white in Set 1, the adaptation luminance increases. On the other hand due to the warm surrounding, the adaptation state of the observer decreases and so adaptation luminance to the eye of the observer. Overall, the presence of a higher blue content in the CWLED spectrum allows for better performance in the mesopic region.

Table 3.16: Effect of different surrounding source type

Average Luminance (in cd/m^2)	Set-1 (CWLED & CWSLS)	Set-2 (CWLED & WWSLS)
L_p	2.53	2.63
L_m	2.72	2.72
L_a	2.78	2.71
Percentage increase in L_a	2.16%	-0.37%

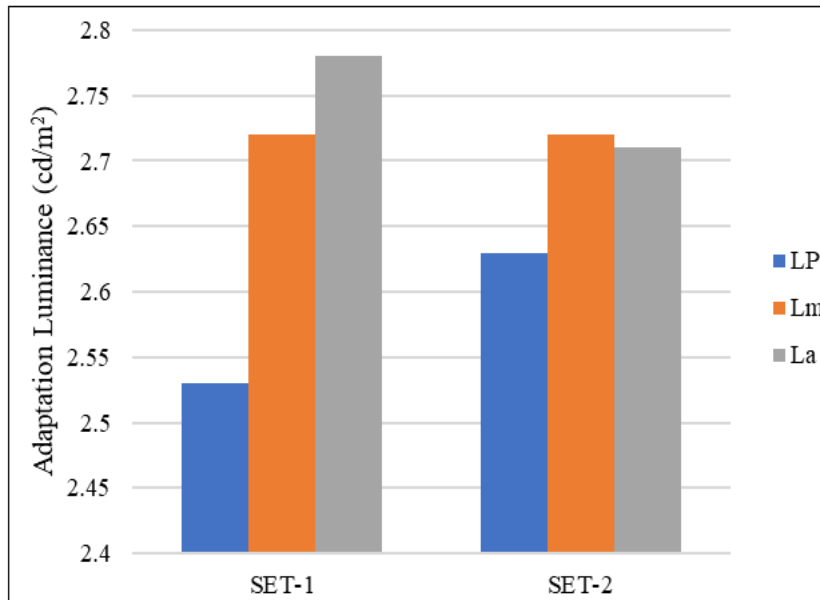


Fig. 3.15: Comparison of average luminance

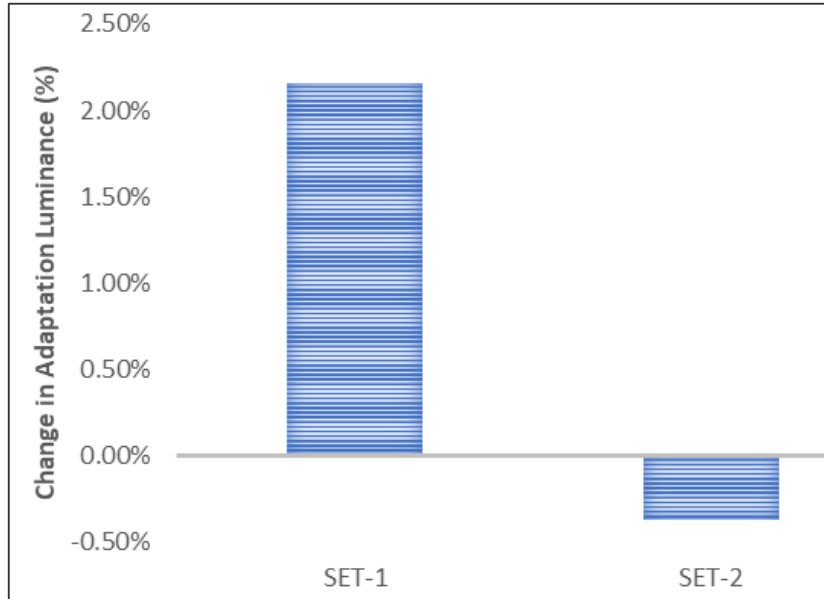


Fig. 3.16: Change in adaptation luminance

The results show that the increment in adaptation state for set 1 when the main light source was cool white LED and the surrounding light source was cool white FTL is 2.16% and for set 2 when the main light source was cool white LED and surrounding light source was warm white FTL is -0.37% as shown in **Fig.3.16**. These findings suggest that the combination of a cool white light source and a cool white surrounding light source leads to a higher increase in adaptation state compared to the combination of a cool white light source and a warm white surrounding light source. This highlights the importance of considering both the main and surrounding light sources when determining the overall adaptation luminance and adaptation field.

3.4 Chapter Summary

Due to the absence of guidelines and instruments to measure the mesopic luminance in the present photometry system and real lighting applications, it is necessary to compute or measure the photopic luminance at first. Corresponding mesopic and adaptation luminance can be computed further according to different methods defined by CIE and other international standards. Here outdoor lighting conditions have been simulated with different light sources that are used in outdoor lighting applications. Cool White LED (CWLED) has been considered as main light source (MLS). Three surrounding light sources (SLSs) (fluorescent lamps) of the same luminous intensity distribution pattern are considered to achieve the effect of surrounding lighting on the application area in a real scenario. These surrounding lighting effects (SLE) have been created for two different conditions i.e. warm white SLS (WWSLS) & cool white SLS (CWSLS). In the next part, mesopic and adaptation luminance have been computed from the corresponding photopic luminance for both the surrounding lighting conditions. In this section, it has been found that

- Cool white LEDs provide better performance in mesopic region as increment in adaptation state for set 1 when the main light source was cool white LED and surrounding light source was cool FTL is 2.16% and for set 2 when the main light source was cool white LED and surrounding light source was warm FTL is -0.37%.
- The surrounding light sources have a significant role on adaptation luminance to observer's eyes. When both the main light source and surrounding sources are of same S/P ratio, then the effective luminance will increase significantly.

The results obtained in this chapter have been utilized in the next chapters to achieve research **objective II**.

- **Publication**

Studies and results discussed in Chapter 3 have been reported in the following publication:

Journal Publications: 1

1. **Sangita Sahana & Biswanath Roy. 2021.** Effect of Chromaticity of Surrounding Light Sources on Mesopic Adaptation Luminance. Published in International Journal “**Light & Engineering**”, Vol.29, No. 1, pp 30-38, 2021, doi: 10.33383/2020-012.

4 Evaluation of Mesopic Adaptation Luminance under Different Surrounding Lighting Ambience

In this work, photopic luminance for the entire field of measurement were measured and corresponding mesopic luminance values are calculated from CIE 191:2010 Table using the scotopic/photopic (S/P) ratio of the installed lamps. Adaptation luminance for the said area of measurement is calculated by the method described in **Chapter 2**. This method takes into account the luminance values of both photopic and mesopic vision to provide a comprehensive understanding of lighting conditions in the area. By considering the S/P ratio and adaptation luminance, a more accurate representation of visual perception in varying light levels can be achieved.

4.1 Introduction

The illumination level of many outdoor application areas belongs to the mesopic vision. Hence it is necessary to evaluate the associated lighting parameters in the mesopic photometry system only. However, due to the unavailability of mesopic meters, photopic quantities are measured first and then these are mapped to corresponding mesopic parameters. Again, in outdoor lighting application areas it is also required to consider adaptation luminance due to user's wide field of view. To get an idea about light distribution in the area of measurement, point specific luminance in photopic and mesopic region are measured and calculated respectively in laboratory environment.

Outdoor lighting condition has been simulated in dark room laboratory environment with different light sources that are mostly used in outdoor lighting applications. Four different types of lamps that are commonly used in outdoor lighting applications i.e. High Pressure Sodium Vapour (HPSV), Metal Halide (MH), White LED (WLED), Cool White LED (CWLED) have been considered as main light source (MLS) as discussed in **Chapter 3**. Three surrounding light sources are also taken into consideration to achieve the effect of surrounding light sources in actual condition. These surrounding lighting effects (SLE) have been created for two different conditions i.e. warm white SLS (WWSLS) and cool white SLS (CWSLS) as discussed in **Chapter 3**.

4.2 Measurement & Computation method for mesopic adaptation luminance

The mesopic lighting environment condition has been experimentally simulated in a darkroom laboratory with one main light source (MLS) and three surrounding light sources (SLS). Computation and measurement of photopic luminance for this arrangement have been repeated

for three other different sets of main light source comprising of commonly used lamp in outdoor lighting applications.

The total area of measurement is divided into 66 grid (0.5m x 0.5m) points under main light source. Point specific photopic luminance values are measured using a Konica Minolta Luminance Meter LS 100 [79] for all the grid points. The following three steps are involved in this present study:

- Measurement of photopic luminance of AOM (L_p)
- Calculation of corresponding mesopic luminance (L_m) and
- Calculation of corresponding adaptation luminance (L_a)

The above steps have been repeated for all possible combinations of main light sources and surrounding sources taken into consideration. The S/P ratio of the lamps are measured by Scotopic/Photopic Ratio (S/P) meter of SOLAR Light [80]. Point specific mesopic luminance values for all the grid points are calculated from corresponding measured photopic luminance using CIE table as shown in **Table 3.4**. The computation of mesopic luminance is carried out using S/P ratio of MLS. On the other hand, the effects of veiling luminance due to SLSs are taken into account to find out the value of adaptation luminance.

4.3 Experimentation and Evaluation

The experimental setup for this work has been developed and discussed in detail below:

- **Experimental Setup**

The outdoor lighting condition has been developed in the laboratory environment for the experimental purpose. **Fig.4.1** shows a diagram of the experimental Set-up used to carry out the experiment in the

Dark Room of Illumination Engineering Laboratory, Electrical Engineering Department of Jadavpur University. Luminaires were fixed on a pole at a height of 3.6m as per the available ceiling height in the laboratory. Luxmeter was mounted firmly on tripod at eye height. The measurement grid was of 11x6 points with both length and breadth wise separation of 0.5m. Length wise the grids were marked as 1,2,...11. Breadth wise the grids were marked as A,B,...F as shown in **Fig. 4.1**. The luminance meter was fixed at height of 1.4m at a distance of 6m from the point (D,6). In this figure the surrounding light source positions are shown as SLE1, SLE2 and SLE3. SLE3 is 0.7m away from grid point (F,1). SLE2 is 0.7m away from grid point(F,8). SLE1 is 2.9m away from SLE2. Mounting height of the surrounding light sources is 2.5m. The nadir point of the main light source is at grid point (B,6). The actual experimental Setup has been shown in **Fig. 4.2**. The details of all the instruments are provided in Annexure 2 [81].

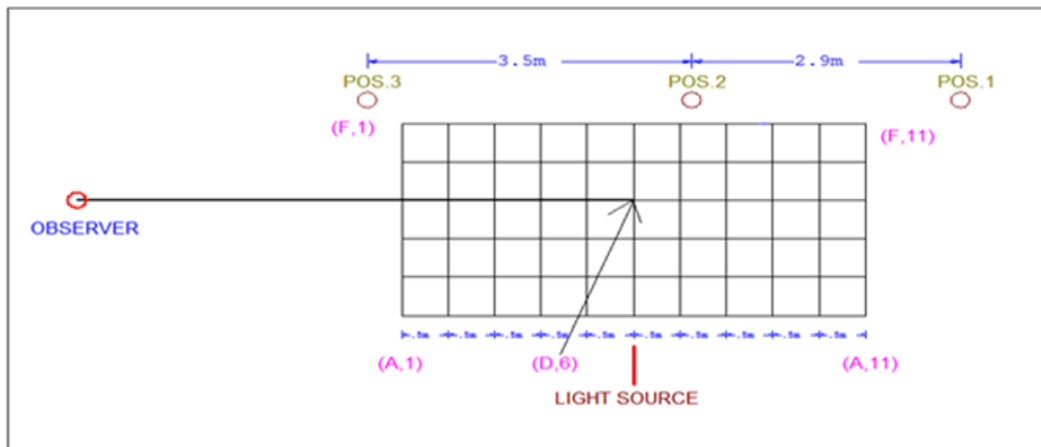


Fig. 4.1: Planview of the luminaire layout and the area of measurement



Fig. 4.2: Experimental Setup

- **Test Conditions**

Each test condition is physically simulated with one MLS and three SLSs. Again for each type of MLS, measurements have been done for two Sets of SLS i.e. WWSLS and CWSLS separately. **Table 4.1** shows the combination matrix of MLS and SLSs. Here 'Y' marks are used to show only a combination of MLS and SLS whereas 'N' marks show none. Point-specific photopic luminance and vertical illuminance are measured on all the grid points for the entire area of measurement using Luminance Meter and luxmeter respectively for two sets of lighting ambiance created by specific combinations of MLS and SLSs as shown in **Table 4.2**.

- **Lamps Used**

Most used lamps in outdoor lighting application areas are considered in this experiment work as MLS. The four different light sources are

Table 4.1: Photopic Luminance measurement conditions

		HPSV	MH	WLED	CWLED
Set 1 CWSLS	All SLS OFF	Y	Y	Y	Y
	CWSLS 1 is on	Y	Y	Y	Y
	CWSLS 2 is on	Y	Y	Y	Y
	CWSLS 3 is on	Y	Y	Y	Y
	All CWSLSs are on	Y	Y	Y	Y
Set 2 WWSLS	All SLS OFF	N	N	N	N
	WWSLS 1 is on	N	N	N	N
	WWSLS 2 is on	N	N	N	N
	WWSLS 3 is on	N	N	N	N
	All WWSLSs are on	Y	Y	Y	Y

Table 4.2: Light Sources under Set 1 and Set 2

	SLS 1	SLS 2	SLS 3
Set1: CWSLS	Y	Y	Y
Set2: WWSLS	Y	Y	Y

as follows:

A.High Pressure Sodium Vapour (HPSV)

B.Metal Halide (MH)

C.White LED (WLED)

D.Cool White LED (CWLED)

All the details of photometric and electrical parameters of these lamps are given in Annexure 3. Photometric parameters of these lamps are shown in **Table 4.3**.

A. High Pressure Sodium Vapour (HPSV)

The spectral power distribution (SPD) of the HPSV lamp is measured using JETI Specbos1200 spectroradiometer [82] and shown below in **Fig. 4.3**.

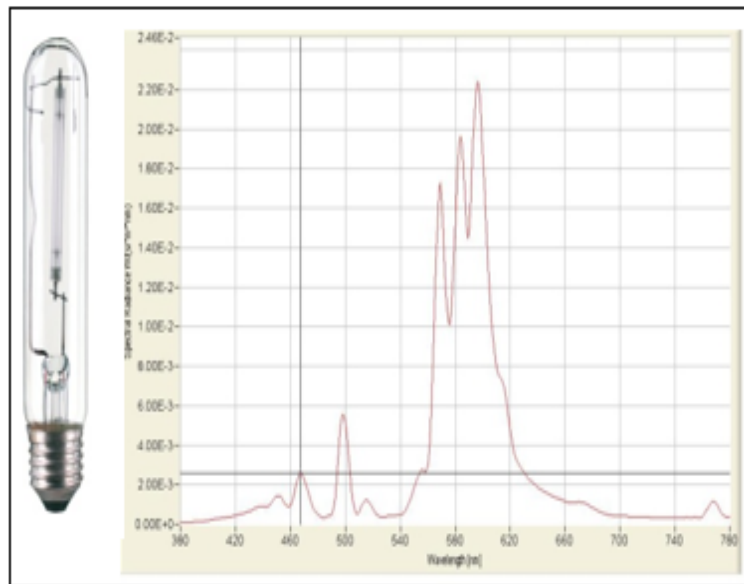


Fig. 4.3: SPD curve of 70W HPSV lamp

B. Metal Halide (MH)

The SPD of the metal halide lamp is measured using spectroradiometer and shown below in **Fig. 4.4**.

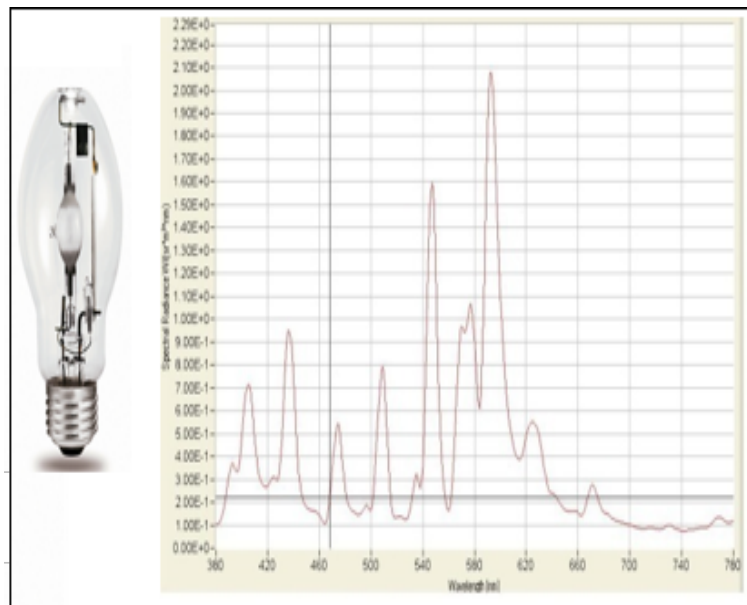


Fig. 4.4: SPD curve for 70W Metal Halide

C. White LED (WLED)

The SPD curve of the white LED has been measured using spectroradiometer and shown below shown in **Fig. 4.5**.

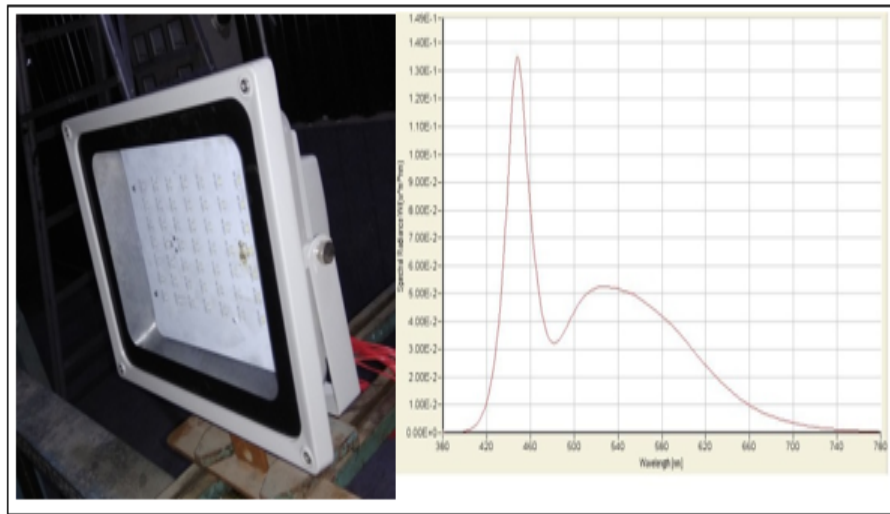


Fig. 4.5: SPD curve for 72W White LED (WLED)

D. Cool White LED (CWLED)

The SPD of the CWLED lamp that is used in this experiment has been measured using spectroradiometer and shown below shown in **Fig. 4.6**.

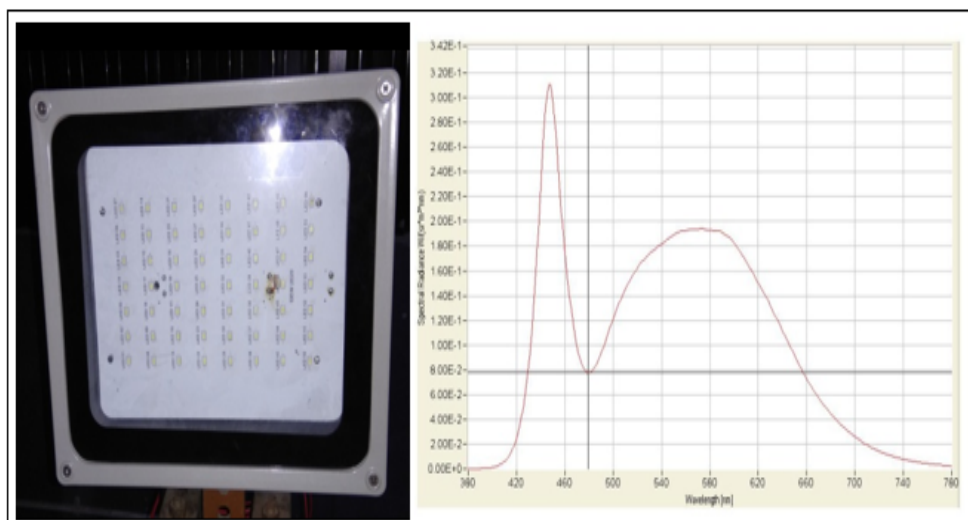


Fig. 4.6: SPD curve for 72W Cool White LED (CWLED)

*** Surrounding Light Sources (SLS)**

Two types of Fluorescent Tube lights (FTL) are used as surrounding light sources:

- A. Cool white FTL
- B. Warm white FTL.

A. Cool White FTL (CWFTL)

The SPD of the CW FTL lamps that are used in this experiment has been measured using spectroradiometer and shown below shown in **Fig. 4.7**.

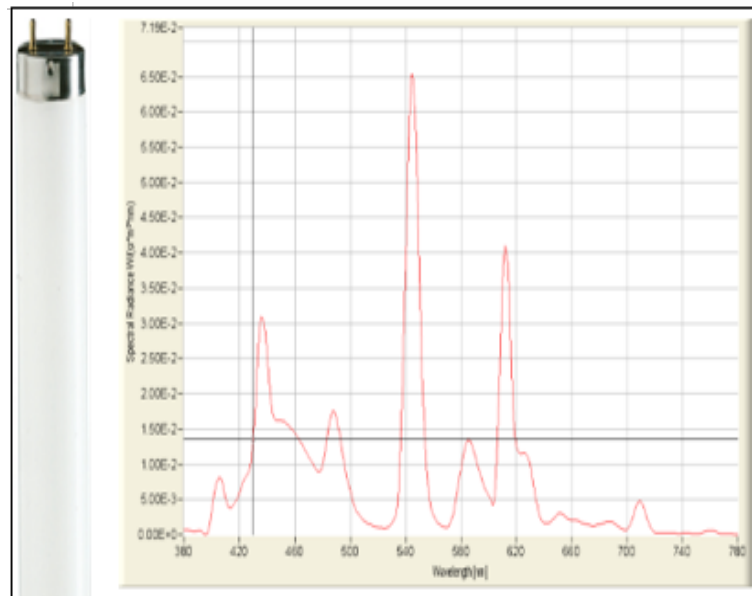


Fig. 4.7: SPD curve for 36W CWFTL

B. Warm White FTL (WWFTL)

The SPD of the WW FTL lamps that are used in this experiment has been measured using spectroradiometer and shown below shown in **Fig. 4.8**.

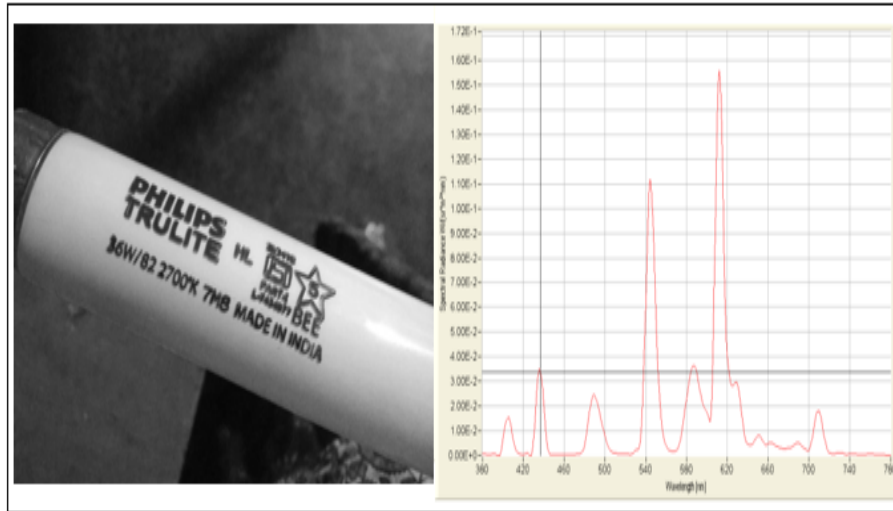


Fig. 4.8: SPD curve for 36W WWFTL

Table 4.3: Measured photometric parameters of MLS and SLS

Technical Specification	A.Main (MLSi)				B.Surrounding (SLSj)	
	1.HPSV	2.MH	3.WLED	4.CWLED	1.CWFTL	2.WWFTL
Lamp Power (watt)	70	70	70	70	36	36
Luminous Flux (lumen)	6000	5600	6000	6000	3250	2450
CRI	35	60	88	83	72	75
CCT (K)	2200	4200	4385	5580	6200	4000
S/P Ratio	0.48	1.32	1.82	2.02	1.86	0.6

4.3.1 Experimental Results

Two Sets of measurements have been done and discussed below:

- **Set 1: CWSLS**

- * **Measurement of Vertical Illuminance**

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 CIE method as discussed in the previous chapter. Vertical illuminance (E_v) due to the SLSs is measured

under three different conditions as shown in **Table 4.2**.

- I. When only SLS1 is on.
- II. When only SLS2 is on.
- III. When only SLS3 is on.

I. Vertical illuminance for SLS1

In this condition only one surrounding light source i.e. SLS1 is glowing along with the MLS. The vertical illuminance due to SLS1 for all the grid points is measured using Luxmeter and listed below in **Table 4.4**:

Table 4.4: Vertical illuminance (in Lux) for SLS1

	A	B	C	D	E	F
1	0.3	0.2	0.1	0.1	0.1	0.1
2	0.5	0.3	0.2	0.1	0.2	0.1
3	0.7	0.6	0.2	0.1	0.2	0.1
4	1.0	0.8	0.4	0.2	0.1	0.1
5	1.4	1.0	0.6	0.3	0.1	0.1
6	1.9	1.8	1.0	1.4	0.1	0.1
7	2.4	2.6	1.7	1.5	0.8	0.1
8	3.9	4.1	3.0	2.9	1.7	0.1
9	5.4	5.9	5.6	5.2	2.4	0.1
10	7.1	7.9	8.6	9.2	6.3	0.1
11	9.9	11.9	14.1	15.3	11.2	0.4

II. Vertical illuminance for SLS2 Here only one surrounding light source i.e. SLS2 is glowing along with the MLS. The vertical illuminance due to SLS2 for all the grid points is measured using Luxmeter and listed below in **Table 4.5**.

III. Vertical illuminance for SLS3

The vertical illuminance due to SLS3 for all the grid points are listed below in **Table 4.6**.

* Measurement of Photopic Luminance (L_p)

Point specific photopic luminance (L_p) values are measured for four different types of main light sources using Luminance Meter for all the

Table 4.5: Vertical illuminance (in Lux) for SLS2

	A	B	C	D	E	F
1	2.3	2.3	1.9	6.5	0.5	0.2
2	2.7	3.1	2.8	10.9	0.6	0.2
3	4.8	4.1	4.5	18.3	2.1	0.4
4	6.5	6.8	7.0	26.1	4.9	1.0
5	8.2	9.7	12.6	26.0	12.5	4.0
6	10.0	13.0	17.6	20.4	24.0	6.0
7	11.2	14.6	20.1	13.0	34.5	11
8	10.5	14.4	18.1	6.1	32.4	10
9	9.7	12.4	15.4	3.0	20.0	5.0
10	7.2	9.4	11.4	2.3	8.6	0.7
11	6.2	7.0	6.1	1.2	3.6	0.6

Table 4.6: Vertical illuminance (in Lux) for SLS3

	A	B	C	D	E	F
1	12.8	20.5	26.7	37.3	43.7	26.2
2	12.1	19	24.6	33.2	39.2	23.9
3	10.3	15.5	17.8	22.3	23.1	12.0
4	9.5	10.9	12.7	14.2	8.7	4.4
5	7.8	8.3	8.9	7.6	4.8	1.0
6	5.6	5.1	5.0	4.3	2.3	0.7
7	3.8	3.5	3.4	2.5	1.2	0.4
8	2.8	2.5	2.0	1.3	0.6	0.1
9	2.2	1.9	1.1	0.9	0.4	0.2
10	1.4	1.1	0.8	0.6	0.3	0.2
11	1.0	0.7	0.6	0.3	0.2	0.2

grid points as discussed in previous section:

A. High Pressure Sodium Vapour (HPSV)

B. Metal Halide (MH)

C. White LED (WLED)

D. Cool White LED (CWLED)

All the measured data for each combination are given in Annexure IV. Only the results for the CWLED as MLS have been shown in this section.

D. For cool white LED (CWLED) Lamp

Photopic luminance has been measured with CWLED lamp for 5 different conditions as shown in **Table 4.2**:

- i. Measurement of L_p when only CWLED is on
- ii. Measurement of L_p when CWLED & SLS1 are on.
- iii. Measurement of L_p when CWLED & SLS2 are on.
- iv. Measurement of L_p when CWLED & SLS 3 are on.
- v. Measurement of L_p when CWLED & all SLSs are on.

The measured photopic luminance for all the grid points have been shown in the below **Table 4.7** for only one combination (v) i.e. when CWLED & all SLSs are on. All the other results are shown in Annexure IV.

v. Measurement of L_p when CWLED & all SLSs are on

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 4.7**.

Table 4.7: Photopic Luminance (in cd/m^2) when CWLED and all SLSs are on

	A	B	C	D	E	F
1	2.67	3.06	3.16	1.32	1.57	1.15
2	3.14	3.66	3.20	2.45	1.63	1.32
3	3.29	3.79	3.10	2.60	1.75	1.37
4	3.61	4.23	3.14	2.68	2.16	1.30
5	3.42	3.85	2.9	2.35	1.86	1.65
6	3.43	4.11	2.82	2.47	1.73	1.37
7	3.49	3.23	2.64	2.25	1.95	1.14
8	2.40	2.64	2.36	1.83	1.60	0.98
9	1.62	1.96	2.20	1.85	1.32	0.96
10	1.47	2.01	1.77	1.28	1.09	0.91
11	1.14	1.30	1.40	1.22	1.99	0.83

The average values of measured photopic luminance are shown in **Table 4.8**.

- **Set 2: WWSLS**

Table 4.8: Photopic Luminance (in cd/m²)for various combination of MLS and SLS

MLS	ONLY MLS	MLS& SLS1	MLS& SLS2	MLS& SLS3	MLS& ALL SLS
HPSV	1.83	1.95	1.97	1.95	2.27
MH	1.65	1.72	1.74	1.72	1.83
WLED	1.79	1.89	1.90	1.92	2.02
CWLED	1.98	2.05	2.12	2.10	2.21

*** Measurement of Vertical Illuminance**

The adaption luminance that the observer perceives is influenced by the veiling luminance produced by the surrounding light sources. The CIE approach, which was covered in the previous chapter, is used to compute veiling luminance. The SLS-induced vertical illuminance (E_v) is evaluated in three different scenarios as shown in **Table 4.2**.

- I. When only SLS1 is on.
- II. When only SLS2 is on.
- III. When only SLS3 is on.

I. Vertical illuminance for SLS1

The MLS and SLS1, both are glowing in this situation. Luxmeter is used to measure each grid point’s vertical illuminance caused by SLS1 and listed below in **Table 4.9**:

II. Vertical illuminance for SLS2 Here only one surrounding light source i.e. SLS2 is glowing along with the MLS. The vertical illuminance due to SLS2 for all the grid points is measured using Luxmeter and listed below in **Table 4.10**.

III. Vertical illuminance for SLS3

The vertical illuminance due to SLS3 for each grid point and listed below in **Table 4.11**.

*** Measurement of Photopic Luminance (L_p)**

The photopic luminance is measured on all the grid points using lumi-

Table 4.9: Vertical illuminance (in Lux) for SLS1

	A	B	C	D	E	F
1	1	0.8	0.3	0.2	0.1	0.1
2	1.1	0.6	0.3	0.1	0.1	0.1
3	1.5	1.2	0.5	0.3	0.1	0.1
4	1.9	1.4	0.8	0.3	0.1	0.1
5	2.6	1.9	1.5	0.6	0.1	0.1
6	3.4	2.8	2.4	1.3	0.2	0.1
7	4.5	3.7	3.4	1.8	0.5	0.1
8	5.8	4.8	4.7	2.9	1.6	0.1
9	7.5	7.2	7.5	5.6	3.1	0.1
10	10.3	10.9	9.4	7.7	5.9	0.1
11	12.8	15.8	18.3	17.7	13.2	0.1

Table 4.10: Vertical illuminance (in Lux) for SLS2

	A	B	C	D	E	F
1	4.8	3.4	3.3	1.9	0.6	0.1
2	6.6	5.7	3.9	3.4	1.7	0.3
3	7.5	7.4	7.1	5.8	3.2	0.2
4	11	10.9	10.8	8.9	6.5	0.2
5	12.9	15.5	18	19.3	16.2	1
6	14.6	17.5	22	26.6	28.5	1.8
7	15.4	20	26	34.6	41.1	0.2
8	15	19.5	25.8	34.9	42.8	1.1
9	13.6	16.2	19	23.4	26.8	3.2
10	11.4	13.6	15.2	17.3	16.4	0.6
11	7.9	8.5	8.9	8.1	6.3	0.3

Table 4.11: Vertical illuminance (in Lux) for SLS3

	A	B	C	D	E	F
1	17.1	23.1	30.7	40.9	47.2	30.6
2	15.5	21.3	27.9	36.6	39.9	26.9
3	14.2	17.6	21	24.3	23.3	15.3
4	11.7	12.6	14.6	14.9	10.9	6.2
5	8.9	9.7	9.5	7.9	5.7	2.1
6	6.4	6.8	6.5	5	3.1	0.4
7	4.9	4.5	3.7	3	1.7	0.3
8	3.4	2.7	2.5	1.6	0.5	0.2
9	2.6	2.1	1.9	1.1	0.2	0.1
10	2.1	1.6	1.2	0.7	0.3	0.1
11	1.4	1	0.9	0.4	0.3	0.1

nance meter. The surrounding effect is created by warm white FTL in all the three positions. The experiment is repeated for all the four different types of main light sources as discussed in previous section. All the measured data for each combination are given in Annexure IV. Only the results with the CWLED as MLS have been shown in this section.

D. For cool white LED (CWLED) Lamp

For CWLED lamp photopic luminance are measured for two different conditions as shown in **Table 4.2**:

- i. Measurement of L_p when only WWLED is on
- ii. Measurement of L_p when WWLED & all SLSs are on.

The measured photopic luminance for all the grid points have shown in the below table for only one combination (v) i.e. when WWLED & all SLSs are on. All the other results are shown in Annexure IV.

ii. Measurement of L_p when CWLED & all SLSs are on

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 4.12**.

All the other measured photopic luminance data for different combination under HPSV, MH & WLED lamps are given in Appendix 4 and only the average values are shown in **Table 4.13**.

4.4 Determination of Mesopic Luminance

As discussed in **Chapter 3**, mesopic luminance (L_m) values have been calculated from the corresponding photopic luminance for both sets i.e. CWSLS & WWSLS using the CIE 191-2010 table as shown in **Table 3.4**. S/P ratio of the lamps are measured by Scotopic/Photopic meter.

Table 4.12: Photopic Luminance (in cd/m^2) when WWLED and all SLSs

	A	B	C	D	E	F
1	2.95	3.48	3.29	2.46	2.04	0.85
2	3.04	3.16	3.08	2.29	1.72	1.28
3	3.07	3.19	2.95	2.77	1.92	1.15
4	2.91	3.29	3.04	2.71	1.94	1.22
5	2.73	2.98	2.72	2.52	1.95	1.31
6	2.85	2.72	2.47	2.32	1.74	1.41
7	2.44	2.72	2.59	2.28	1.75	1.23
8	2.19	2.42	2.36	1.75	1.38	1
9	1.52	1.98	2.29	1.71	1.19	0.82
10	1.29	1.59	1.94	1.42	0.96	0.83
11	1.06	1.28	1.41	1.19	0.8	0.62

Table 4.13: Photopic Luminance (in cd/m^2) for various combination of MLS and SLSs

MLS	ONLY MLS	MLS & ALL SLS
HPSV	1.83	2.09
MH	1.65	1.87
WLED	1.79	2.11
CWLED	1.98	2.05

Then mesopic luminance values are interpolated from the known photopic luminance values and S/P ratios using the table. All the mesopic luminance of the corresponding photopic luminance for various combination of MLS and SLSs as shown in **Table 4.2** are calculated using this method.

• **Set 1: CWSLS**

Point specific mesopic luminance (L_{mes}) values are calculated for all the grid points for four different types of main light sources from the measured data shown in **section 4.4**:

- A. High Pressure Sodium Vapour (HPSV)
- B. Metal Halide (MH)
- C. White LED (WLED)
- D. Cool White LED (CWLED)

The calculated mesopic luminance of all the grid points have shown in the below table for only one combination i.e. when CWLED & all SLSs are on. All the other results are shown in Appendix 4.

D. For cool white LED (CWLED) Lamp

Mesopic luminance values are calculated for CWLED lamp along with all the SLSs from the corresponding measured photopic luminance data and listed below in **Table 4.16**:

Table 4.14: Mesopic luminance (in cd/m²) with CWLED and all SLSs

	A	B	C	D	E	F
1	2.76	3.14	3.24	1.42	1.67	1.25
2	3.22	3.72	3.28	1.67	1.73	1.42
3	3.36	3.84	3.18	2.69	1.85	1.47
4	3.67	4.27	3.22	2.77	2.25	1.4
5	3.49	3.9	2.98	2.44	1.96	1.75
6	3.5	4.15	2.91	2.56	1.83	1.47
7	3.55	3.3	2.73	2.34	2.04	1.24
8	2.49	2.73	2.45	1.93	1.7	1.08
9	1.72	2.05	2.29	1.95	1.42	1.06
10	1.57	2.1	1.87	1.38	1.19	1.01
11	1.24	1.4	1.5	1.32	2.08	0.93

All the other calculated mesopic luminance for different combination under HPSV, MH & WLED lamps are given in Appendix and only the average mesopic luminance values are shown in **Table 4.15**.

Table 4.15: Mesopic Luminance (in cd/m²) for various combination of MLS and SLS

MLS	MLS & all SLSs
HPSV	2.22
MH	1.86
WLED	2.09
CWLED	2.29

- **Set 2: WWSLS**

Point specific mesopic luminance (L_{mes}) values are calculated for all the grid points for four different types of main light sources from the measured data shown in **section 4.4**.

D. For cool white LED (CWLED) Lamp

Mesopic luminance values are calculated for CWLED lamp along with all the SLSs from the corresponding measured photopic luminance data and listed below in **Table 4.16**.

Table 4.16: Mesopic luminance (in cd/m^2) with CWLED and all SLSs

	A	B	C	D	E	F
1	3.03	3.55	3.36	2.55	2.13	0.94
2	3.12	3.24	3.16	2.38	1.82	1.38
3	3.15	3.27	3.03	2.86	2.01	1.25
4	3	3.36	3.12	2.8	2.03	1.32
5	2.82	3.06	2.81	2.61	2.04	1.41
6	2.94	2.81	2.56	2.41	1.84	1.51
7	2.53	2.81	2.68	2.29	1.85	1.33
8	2.28	2.51	2.45	1.85	1.48	1.10
9	1.62	2.07	2.38	1.81	1.29	0.91
10	1.39	1.69	2.03	1.52	1.06	0.92
11	1.16	1.38	1.51	1.29	0.89	0.70

The average values are shown in **Table 4.17**.

Table 4.17: Mesopic Luminance (in cd/m^2) for various combination of MLS and SLSs

MLS	MLS & all SLSs
HPSV	2.01
MH	1.91
WLED	2.19
CWLED	2.15

4.5 Determination of Adaptation Luminance

The adaptation luminance for all the combinations of **Table 4.2** are computed using MATLAB software after the measurement of photopic

luminance & calculation of mesopic luminance and discussed below. There are two Sets as discussed in previous section. Photopic Luminance (L_p) and Veiling Luminance (L_{veil}) of each grid points are added to get Adaptation Luminance (L_a).

- **Set 1: CWSLS**

Point specific adaptation luminance (L_a) values are calculated for all the grid points for four different types of main light sources from the measured data as discussed previously:

D. For cool white LED (CWLED) Lamp

Adaptation luminance values are simulated for CWLED lamp along with the effect of SLSs using MATLAB software. The coding in M-file is shown in Appendix 3. Adaptation luminance for all the grid points is listed in **Table 4.18**.

Table 4.18: Adaptation luminance (in cd/m^2) with CWLED and all SLS

	A	B	C	D	E	F
1	2.52	2.85	2.9	2.21	1.57	1.26
2	2.85	3.4	2.94	2.36	1.67	1.31
3	3.18	3.6	2.84	2.69	1.79	1.36
4	3.4	3.76	3.01	2.84	1.79	1.36
5	3.27	3.49	2.8	2.47	2.06	1.71
6	3.21	3.49	2.81	2.63	2.31	1.6
7	2.83	3.26	2.74	2.3	2.94	1.57
8	2.46	2.77	2.56	1.83	2.66	1.4
9	1.79	2.08	2.35	1.93	2.1	1.14
10	1.5	1.9	2.02	1.78	1.82	0.9
11	1.23	1.5	1.81	1.85	1.93	0.87

The average values are shown in **Table 4.19**.

- **Set 2: WWSLS**

Table 4.19: Adaptation Luminance (in cd/m^2) for various combination of MLS and SLS

MLS	ONLY MLS	MLS& SLS1	MLS& SLS2	MLS& SLS3	MLS& ALL SLS
HPSV	1.83	2.01	1.97	2.14	2.31
MH	1.65	1.83	1.78	1.96	2.13
WLED	1.79	2.01	1.97	2.14	2.29
CWLED	1.98	2.15	2.09	2.29	2.41

Point specific adaptation luminance (L_a) values are calculated for all the grid points for 4 different types of main light sources from the measured data.

D. For cool white LED (CWLED) Lamp

Adaptation luminance values are simulated for CWLED lamp along with the effect of all three WWSLSs using MATLAB software and is listed in **Table 4.20**.

Table 4.20: Adaptation luminance (in cd/m^2) with CWLED and all SLSs

	A	B	C	D	E	F
1	2.57	3.02	2.80	2.20	1.69	0.98
2	2.65	2.81	2.71	1.91	1.56	1.36
3	2.76	2.84	2.56	2.34	1.77	1.20
4	2.60	2.85	2.66	2.32	1.84	1.20
5	2.50	2.74	2.48	2.32	2.09	1.30
6	2.55	2.51	2.33	2.30	2.33	1.34
7	2.22	2.51	2.54	2.54	2.82	1.17
8	2.03	2.26	2.35	2.21	2.85	1.02
9	1.46	1.93	2.19	1.95	2.24	0.92
10	1.24	1.70	1.91	1.89	1.93	0.78
11	1.14	1.42	1.87	2.01	1.97	0.60

All the other calculated adaptation luminance for different combination under HPSV, MH & WLED lamps are given in Appendix and only the average values are shown in **Table 4.21**.

Table 4.21: Adaptation Luminance (in cd/m^2) for various combination of MLS and SLSs

MLS	MLS & all SLSs
HPSV	1.99
MH	1.89
WLED	2.15
CWLED	2.17

4.6 Comparative Analysis

Distribution of photopic, mesopic & adaptation luminance over the entire area of measurement have been shown below for both cool white and warm white surrounding lighting conditions.

- **Set 1: CWSLS**

A: Luminance Distribution for HPSV

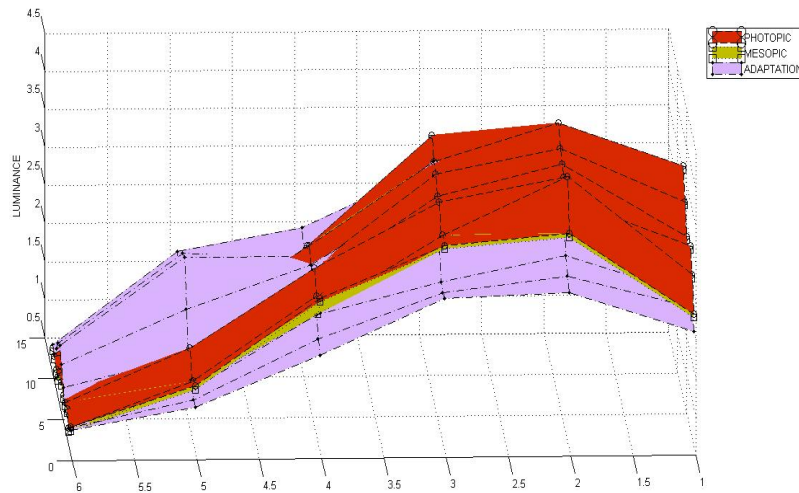


Fig. 4.9: Luminance Distribution for HPSV

When the HPSV is used as MLS with all the surrounding light sources the surface plot is shown below in **Fig.4.9**. Here, Surface plot for photopic luminance is shown in red, mesopic luminance is shown in yellow and adaptation luminance is shown in purple colour. Here it can be observed that photopic luminance values are greater than

mesopic values on all the points of AOM. Adaptation values are lower near the main light source and greater than photopic and mesopic values near the surrounding light sources.

B. Luminance Distribution for MH

The surface plot is shown below in **Fig.4.10** when MH has been used as MLS and all the surrounding light sources are also on. Here it can be observed that photopic luminance values are lesser than mesopic values on all the points of AOM as the S/P ratio is more than 1 i.e. the blue light content in its spectrum is higher as compared to HPSV lamp. Adaptation values are lower near the main light source and greater near the surrounding light sources.

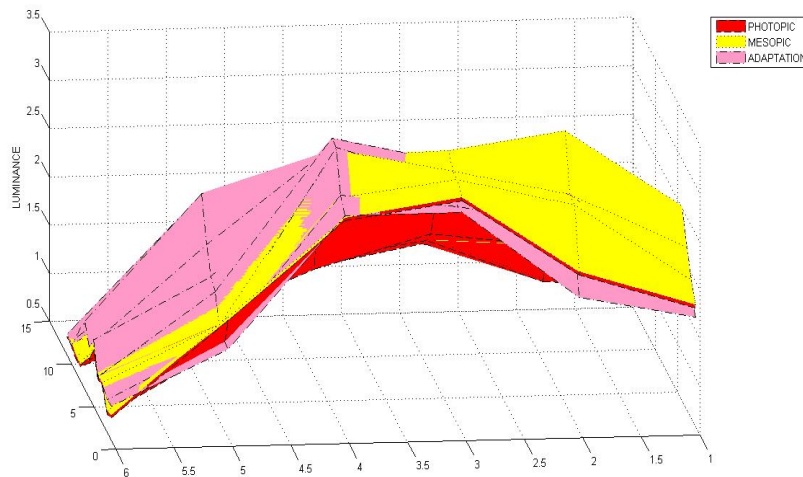


Fig. 4.10: Luminance Distribution for MH

B. Luminance Distribution for WLED

When all the surrounding light sources are also on along with WLED as MLS, the surface plot is shown below in **Fig.4.11**. It can be observed that photopic luminance values are lesser than mesopic values in all the points. Adaptation values are lower near the main light source and greater near the surrounding light sources in the AOM.

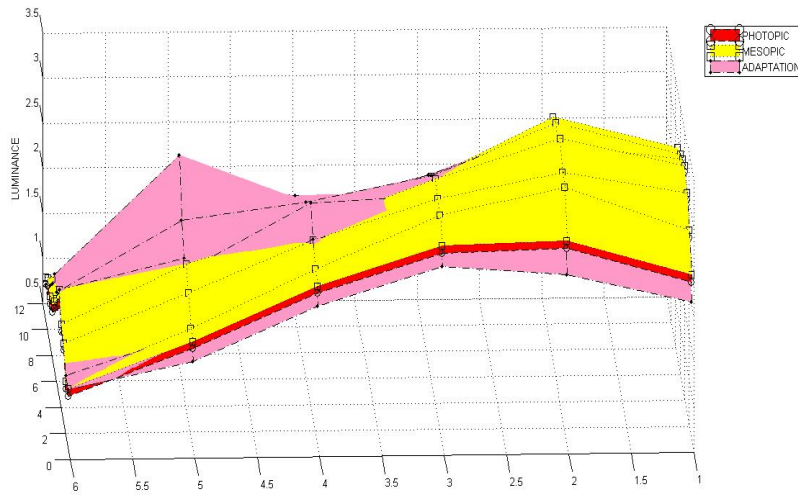


Fig. 4.11: Luminance Distribution for WLED

B. Luminance Distribution for CWLED

For the CWLED and all the surrounding light sources the surface plot is shown below in **Fig.4.12**. Here photopic luminance values are lesser than mesopic values in all the points. Adaptation values are lower near the main light source and are greater than photopic and mesopic values near the surrounding light sources.

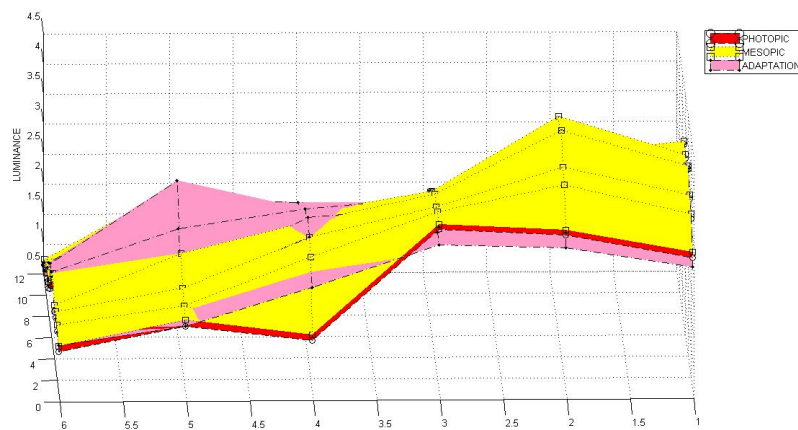


Fig. 4.12: Luminance Distribution for CWLED

- Set 2: WWSLS

A: Luminance Distribution for HPSV

For HPSV when all the surrounding light sources are also on, the surface plot is shown below in **Fig.4.13**. Here photopic luminance values are greater than mesopic values in all the points. Adaptation values are lower near the main light source and greater than photopic and mesopic values near the surrounding light sources.

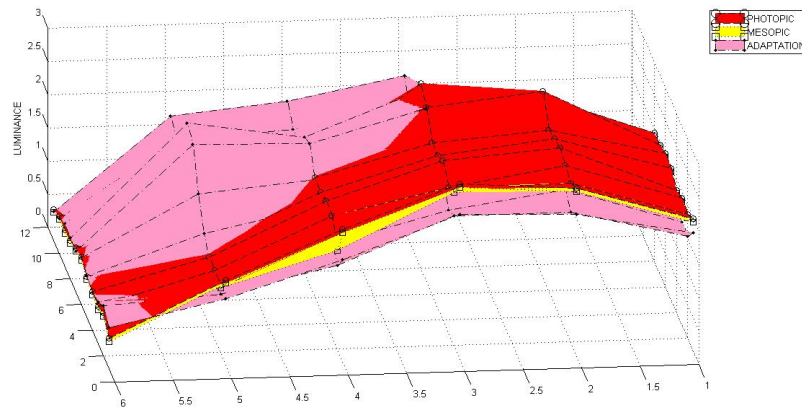


Fig. 4.13: Luminance Distribution For HPSV

B. Luminance Distribution for MH

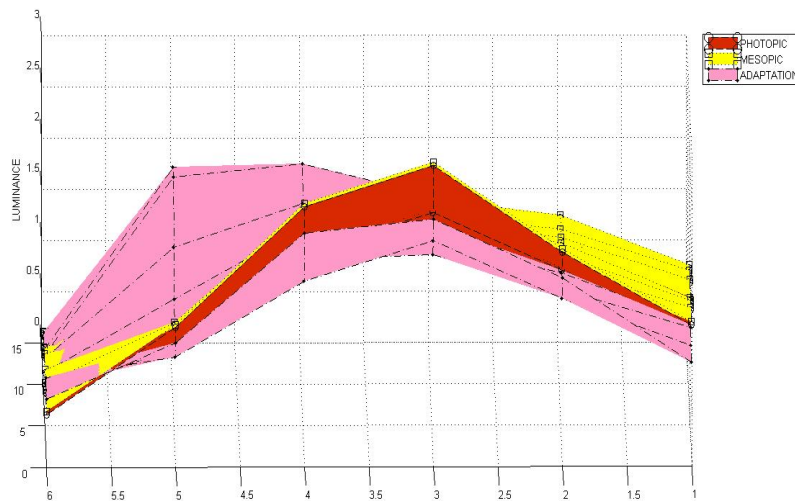


Fig. 4.14: Luminance Distribution For MH

For MH lamp when all the surrounding light sources are also on, the surface plot is shown in **Fig.4.14**. Here the photopic values are lesser

than Mesopic values in all the points. Adaptation values are lower near the main light source and greater than photopic and mesopic values near the surrounding light sources.

B. Luminance Distribution for WLED

For WLED as MLS the surface plot is shown below in **Fig.4.15**. The photopic luminance values are lesser than mesopic values in the entire AOM. Adaptation values are lower near the main light source and greater than photopic and mesopic values near the surrounding light sources.

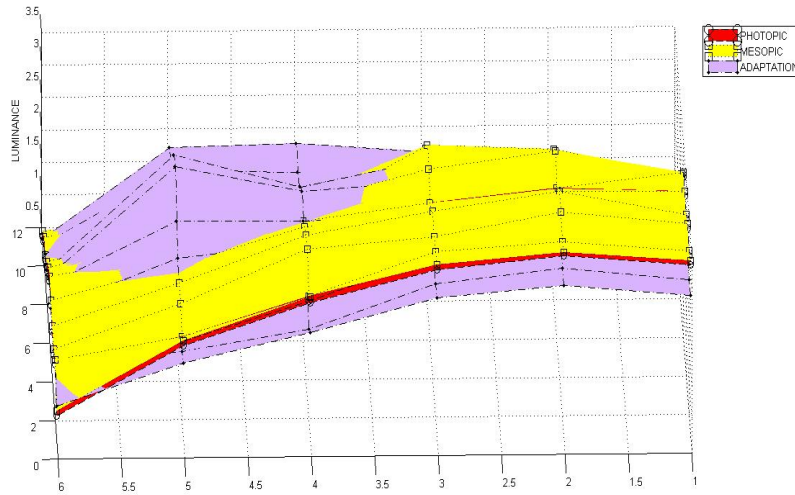


Fig. 4.15: Luminance Distribution For WLED

B. Luminance Distribution for CWLED

For the CWLED and all the surrounding light sources the surface plot is shown below in **Fig.4.16**. Here photopic luminance values are lesser than mesopic values in all the points. Adaptation values are lower near the main light source and are greater than photopic and mesopic values near the surrounding light sources.

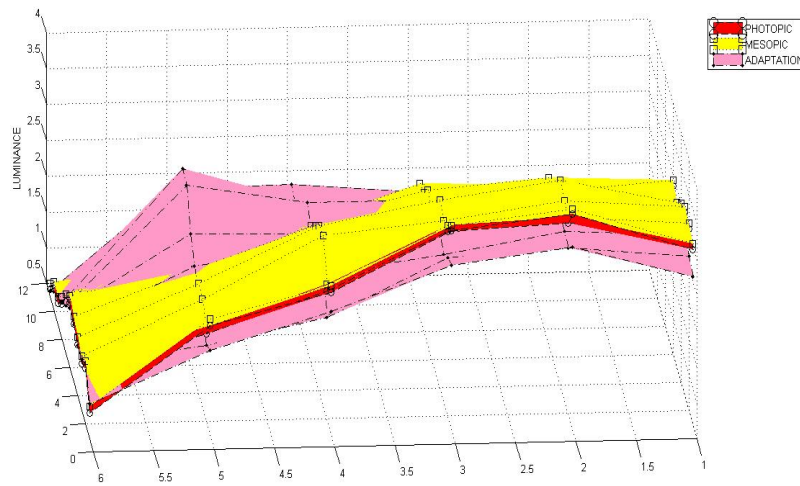


Fig. 4.16: Luminance Distribution For CWLED

From all the figures above it can be stated that mesopic luminance is more effective than adaptation luminance near the main light source where the light level is higher with respect to other areas within the field of view. But adaptation luminance is dominant one near the surrounding light sources i.e. the areas with lower light level. Therefore in any area where veiling sources are present in line of sight it is better to consider adaptation luminance over mesopic luminance.

4.7 Chapter Summary

The use of various light sources in outdoor lighting applications is crucial for creating the desired effect and performance. In this chapter a detailed study has been done to understand the effect of surrounding light sources on the lighting ambience created by different types of MLS such as HPSV, MH, WLED, CWLED. In addition to the primary light sources, three surrounding light sources (SLSs) are also considered for two different conditions to achieve the effect of surrounding light sources on the application area in real scenario: warm white SLS (WWSLS) and cool white SLS (CWSLS). To achieve these conditions, three fluorescent lamps with identical luminous intensity distribution patterns are utilized as SLSs. As at present no such instruments are commercially available to measure the mesopic and adaptation luminance, they are computed from the corresponding measured photopic luminance for both the surrounding lighting conditions. In this section it has been found that

- Cool white LEDs provides better performance in mesopic region as increment in adaptation state for Set 1 when the main light source was cool white LED and surrounding light source was cool FTL is 3.65% and for Set 2 when the main light source was cool white LED and surrounding light source was warm FTL is 2.47%. The surrounding light sources have a significant role on adaptation luminance to observer's eyes. When both the main light source and surrounding sources are of same S/P ratio, then the effective luminance will increase significantly.
- This increase in effective luminance can be attributed to the additive effect of the main light source and surrounding sources with the same S/P ratio. When both the main light source and surrounding sources emit light with a similar spectral power dis-

tribution, they enhance each other's impact on adaptation state of the observer. These findings highlight the significant role that surrounding light sources play in influencing adaptation luminance to an observer's eyes. By carefully considering and aligning the S/P ratios of both main and surrounding light sources, it is possible to achieve a substantial increase in effective luminance, thereby optimizing visual performance.

- Mesopic luminance is more effective than adaptation luminance near the main light source where the light level is higher with respect to other areas within the field of view. But adaptation luminance is dominant one near the surrounding light sources i.e. the areas with lower light level.
- Mesopic luminance seems to be more effective when it comes to the main light source, where the light level is significantly higher compared to other areas in the field of view. This means that in those specific locations, mesopic luminance should take precedence.
- However, when dealing with surrounding light sources or areas with lower light levels, adaptation luminance emerges as the dominant factor. These regions require a different approach, as considering adaptation luminance over mesopic luminance proves to be more suitable.
- It is important to carefully assess the presence of veiling sources within the line of sight to ensure optimal lighting conditions for various environments and enhance visual comfort and clarity.

The results obtained in this chapter have been utilized in the next chapters to achieve research objective II. To investigate the performance of different light sources with different S/P ratios in real field applications considering mesopic dimensioning.

- **Publication**

Studies and results discussed in Chapter 3 have been reported in the following publication:

Journal Publications: 1

1. **Sangita Sahana**, Ananya Paul & Biswanath Roy. **2019**. Adaptation luminance variation under lamps of different spectral compositions with variable surrounding luminance effects. Published in International Journal “**Journal of Optics**”, Vol.48, pp 527-538, 2019, doi: 10.1007/s12596-019-00560-y.

5 Effect of chromaticity of surrounding light sources on Mesopic Adaptation Luminance

To establish adaptation brightness and viewing conditions based on observers' peripheral adaptation state for the use of mesopic photometry systems in outdoor illumination, studies on adaptation features are carried out. In this chapter, it is studied that how different combinations of lamps with varying spectral compositions affect adaption brightness, as well as how warm and cool white light sources affect ambient luminance. The findings highlight the importance of considering both spectral composition and adaption luminance when designing outdoor illumination systems for optimal visual comfort and performance. By considering the adaption luminance for fixed area measurements, designers can ensure that the lighting levels are appropriate for the specific task or activity. Additionally, taking into account the spectral composition of surrounding light sources can help to create a more cohesive and aesthetically pleasing lighting design.

5.1 Introduction

Different chromaticity can affect the perception of brightness and colour, leading to variations in how well individuals adapt to low light conditions. Research has shown that certain chromaticity of light sources can enhance or reduce mesopic adaptation, highlighting the importance of considering the spectral characteristics of surrounding light sources in designing lighting environments for optimal visual performance. To determine adaptation luminance and viewing conditions based on observers' peripheral adaptation state for the use of mesopic photometry systems in outdoor illumination, studies on adaptation features are carried out. In this chapter, experiments are conducted to find how different combinations of lamps with varying spectral compositions affect adaptation state, as well as how warm and cold white light sources affect ambient luminance. According to an analysis of the experiment's data, adaptation luminance should be taken into account for fixed area measurements rather than mesopic luminance.

5.2 Surrounding Luminance Effect on Photopic Luminance

The four different types of lamps used as MLS in this work are high pressure sodium vapor (HPSV) lamp, metal halide (MH), cool white LED (CWLED) and white LED (WLED). The HPSV lamp emits a yellowish-orange light, while the Metal Halide (MH) lamp produces a bluish-white light. On the other hand, the Cool White LED (CWLED) emits a bluish white light, and the White LED (WLED) produces neutral white light. These differences in emission spectrum or SPD allow for various applications and lighting preferences as these are different from each other in terms of their emission spectrum or SPD. The lamp with higher S/P ratio has more blue content in its SPD and emit bluish white light. On the other hand, the lamp with lower S/P ratio has less blue and more yellow colour in its spectrum and hence emits yellowish-

white light. As described in **Chapter 4**, the mesopic lighting environment condition has been experimentally developed in a darkroom laboratory with one main light source (MLS) and three surrounding light sources (SLS). Computation and measurement of photopic, mesopic and adaptation luminance for this arrangement have been repeated for three other different Sets of main light source comprising commonly used lamp in outdoor lighting applications. Comparison of point-specific photopic luminance as computed from illuminance data and measured photopic luminance of the grid points are shown in **Fig. 5.1** and **Fig. 5.2** for cool and warm white surrounding lighting respectively. Here it is also observed that the calculated as well as measured average luminance of CWLED with CWSLS is highest as compared to the other three lamps. The measured value is less than the calculated value due to various environmental effects such as absorption, reflection from various adjacent surfaces, room conditions etc. However, this difference is within the range of 2%-5%, which is acceptable in this case. The same process is repeated for yellowish surrounding light and the difference between calculated and measured photopic luminance values are also in the range of 2%-6% only.

5.3 Surrounding Luminance Effect on Mesopic Luminance

Since the mesopic photometry system relies on peripheral tasks, the effective mesopic luminance for the area being measured must be calculated using adaption luminance. The impact of the spectral composition of bright surrounding sources other than the main light sources on the observer's adaption state was examined in a variety of lighting environments as discussed in **chapter 4**. The observer's adaption state is enhanced by the surrounding sources' veiling of light, but not the brightness inside the measurement field.

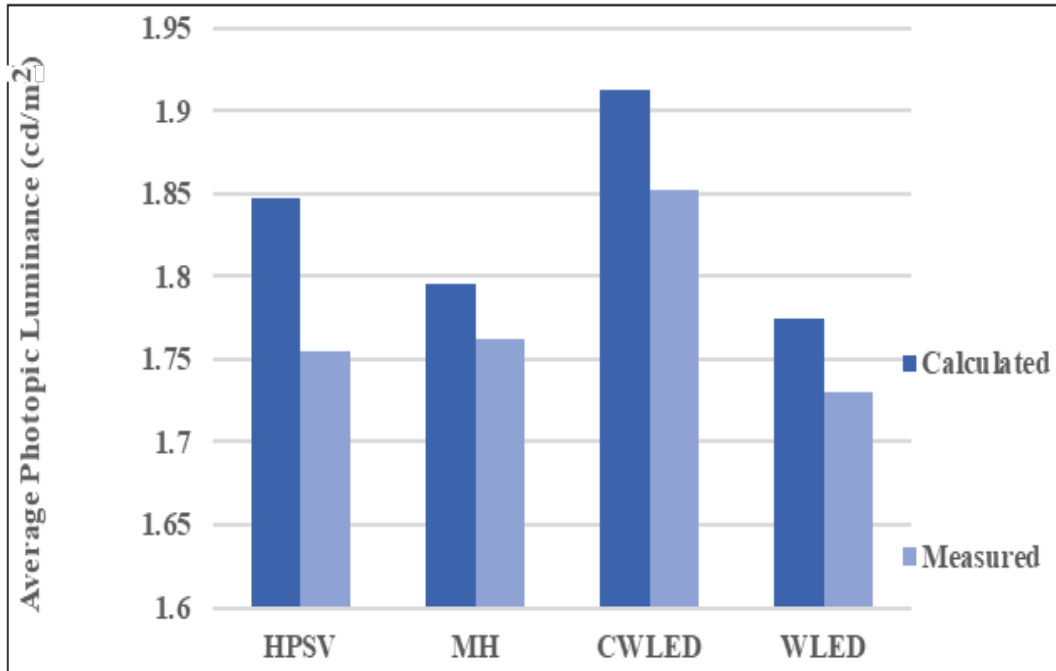


Fig. 5.1: Comparison of average photopic luminance with MLS and CWSLS

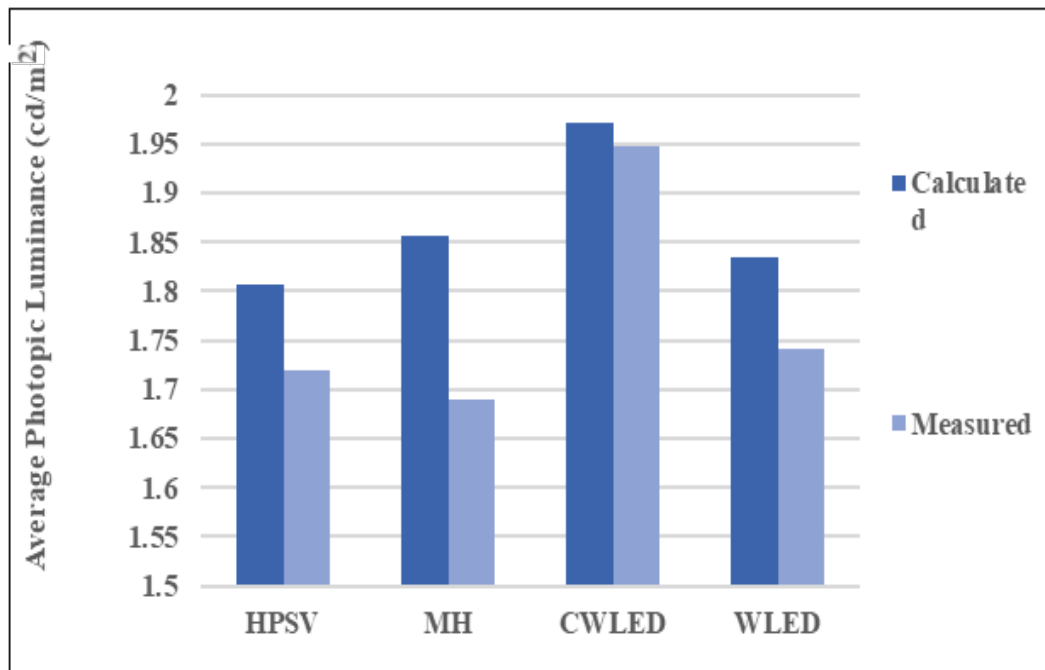


Fig. 5.2: Comparison of average photopic luminance with MLS and WWSLS

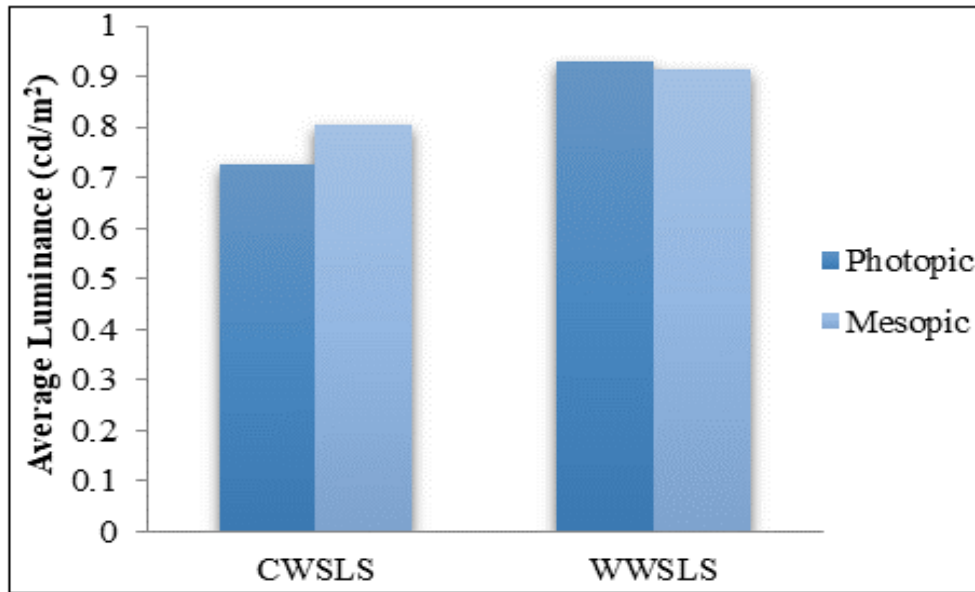


Fig. 5.3: Average Luminance of surrounding sources

In this work the variation of mesopic luminance has been studied considering the S/P ratio of main light sources, as well as of surrounding light sources. Average photopic and mesopic luminance for the entire area of measurement under only two different surrounding lighting effects i.e. CWSLS & WWSLS are shown in **Fig. 5.3**. The mesopic luminance is higher than photopic luminance for CWSLSs, due to higher S/P ratio of 1.86 & lower than the photopic luminance in case of WWSLSs due to lower S/P ratio of 0.60. This statement is justified as per CIE191:2010 recommended table. Therefore, the CWSLSs provide higher mesopic luminance compared to photopic luminance and enhances visibility under low light conditions.

Point specific mesopic luminance values are computed from the corresponding computed photopic luminance table for all the grid points and the average values are shown in **Fig. 5.4** and **Fig. 5.5** for warm and cool surrounding respectively. From the figures it can be stated that when S/P ratio of the main light source of any application area and surrounding sources are not matching, then their effect will cancel

each other. Therefore, effective luminance in both cases will remain same. But when S/P ratios of both the main light source of any application area are matching, then the effective luminance will increase significantly. It is also observed that the calculated and measured average mesopic luminance of CWLED with cool SLS is highest because CWLED as main source has more bluish content and CWFTL as surrounding source has S/P ratio greater than 1 which has good impact on main source providing more effective lighting to the eye of the observer.

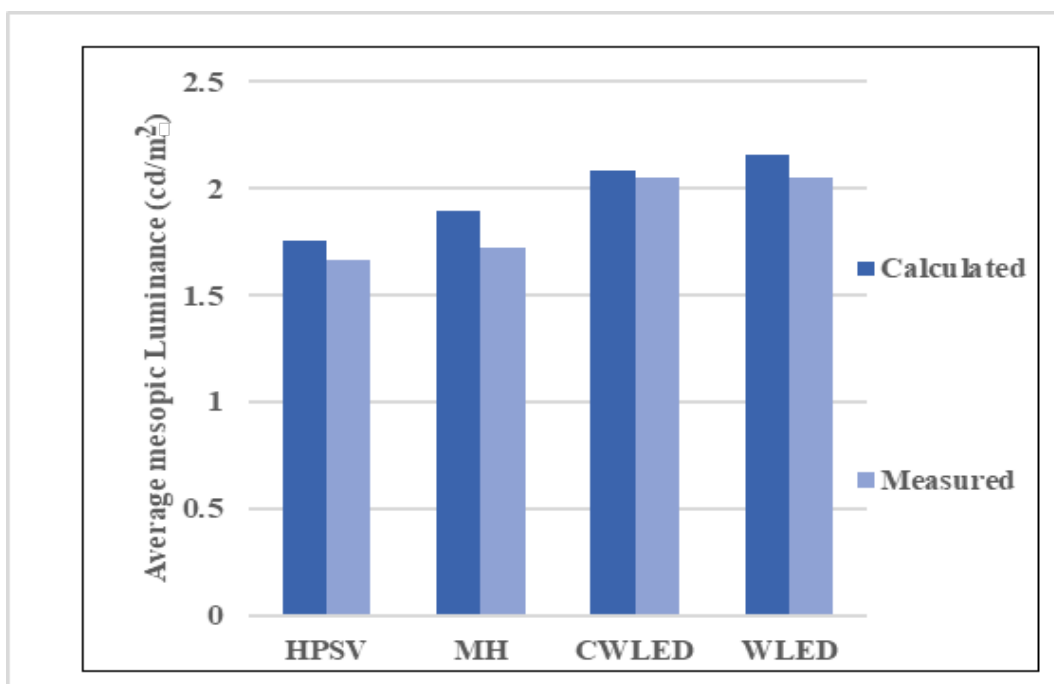


Fig. 5.4: Comparison of average mesopic luminance with MLS and CWSLS

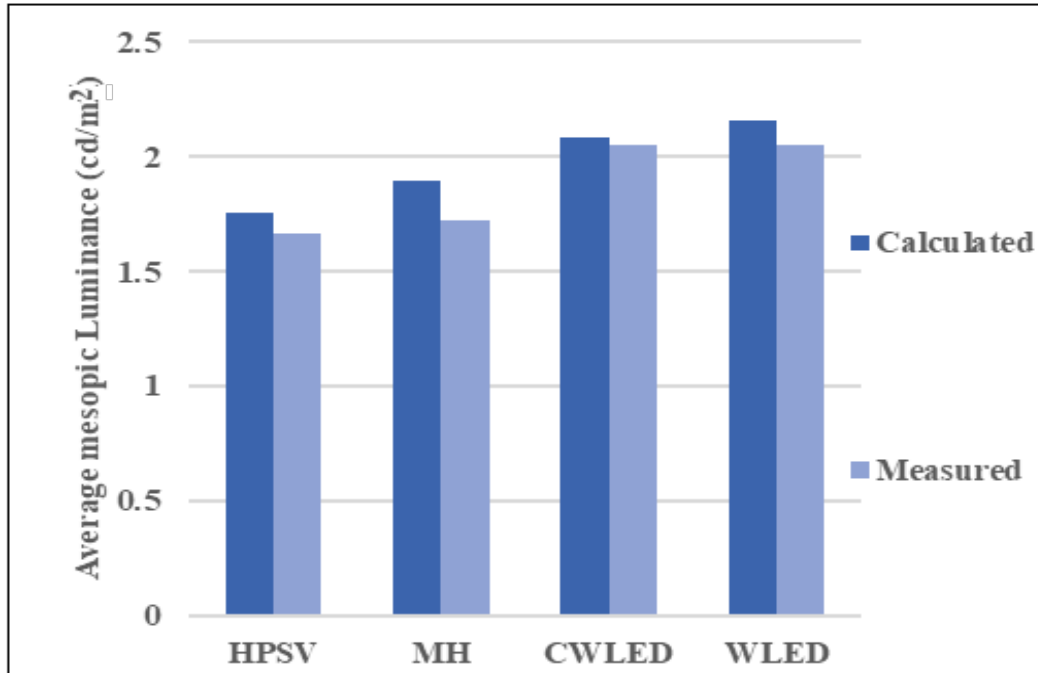


Fig. 5.5: Comparison of average mesopic luminance with MLS and WWSLS

5.3.1 S/P ratio of MLS or SLS: Relative Influence

The calculation of mesopic luminance from corresponding photopic luminance requires the S/P ratio of the used lamps as described in CIE 191:2010. In this work, there are two different types of lamps are providing illumination to the area of measurement. Hence it is necessary to consider the S/P ratio of both the lamps i.e. MLS and SLS. At first mesopic luminance is calculated using the S/P ratio of MLS and then it's again calculated using the S/P ratio of both MLS and SLS separately. These values are added to get the total mesopic luminance of the AoM. In presence of both SLSs and MLS, the results have been presented in **Fig. 5.6** with three sets of data, where HPSV lamp is the MLS. The mesopic luminance is less than photopic luminance due to its lower S/P ratio of 0.61. The photopic luminance has been measured when the main light source and surrounding light source both are lit together. Mesopic luminance, the middle bar was

calculated directly using CIE Table considering the S/P ratio of HPSV only, ignoring S/P ratio of the surrounding sources. The combined mesopic luminance, the third bar, is obtained when main light source and surrounding light sources are switched on separately and mesopic luminance values are calculated separately from measured photopic luminance by considering the corresponding S/P ratio of each lamp. These two individual mesopic luminance values are added to get the combined mesopic effect in the third bar in accordance with Abney's law. This above procedure has been repeated for three other types of MLS i.e. MH, WLED & CWLED and shown below in **Fig. 5.7**, **Fig. 5.8** and **Fig. 5.9** respectively.

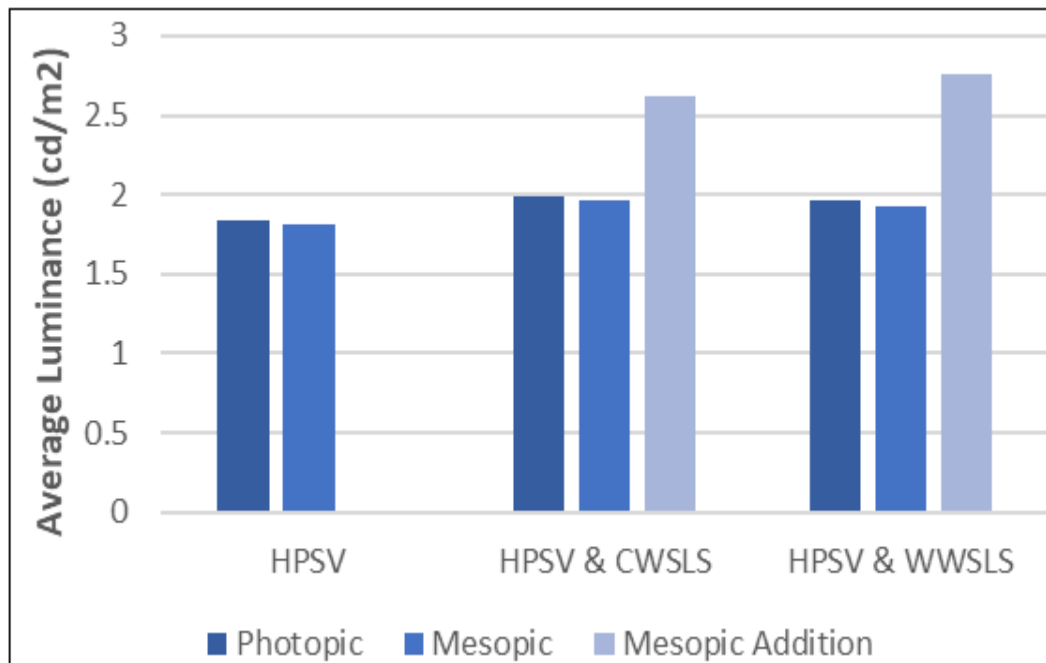


Fig. 5.6: Comparison of Photopic and Mesopic Luminance for HPSV

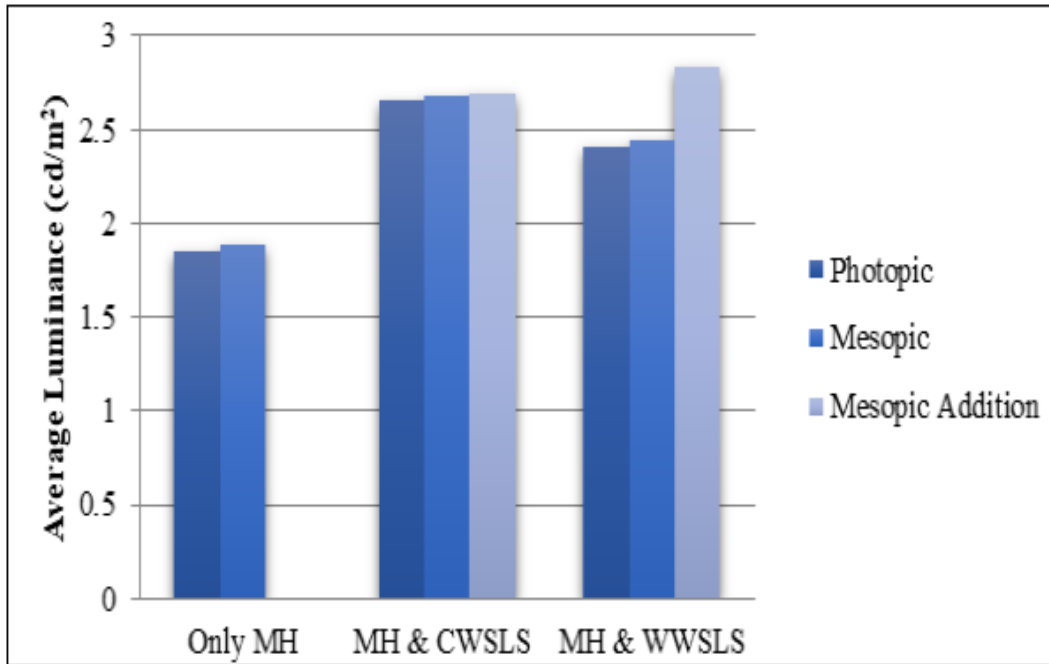


Fig. 5.7: Comparison of Photopic and Mesopic Luminance for MH

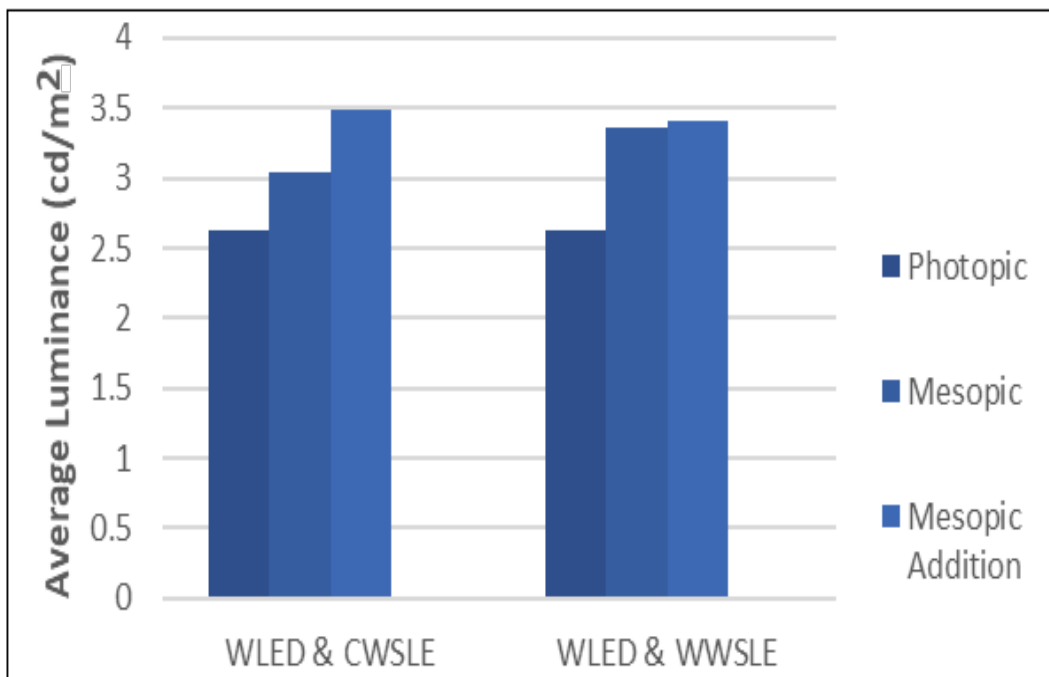


Fig. 5.8: Comparison of Photopic and Mesopic Luminance for WLED

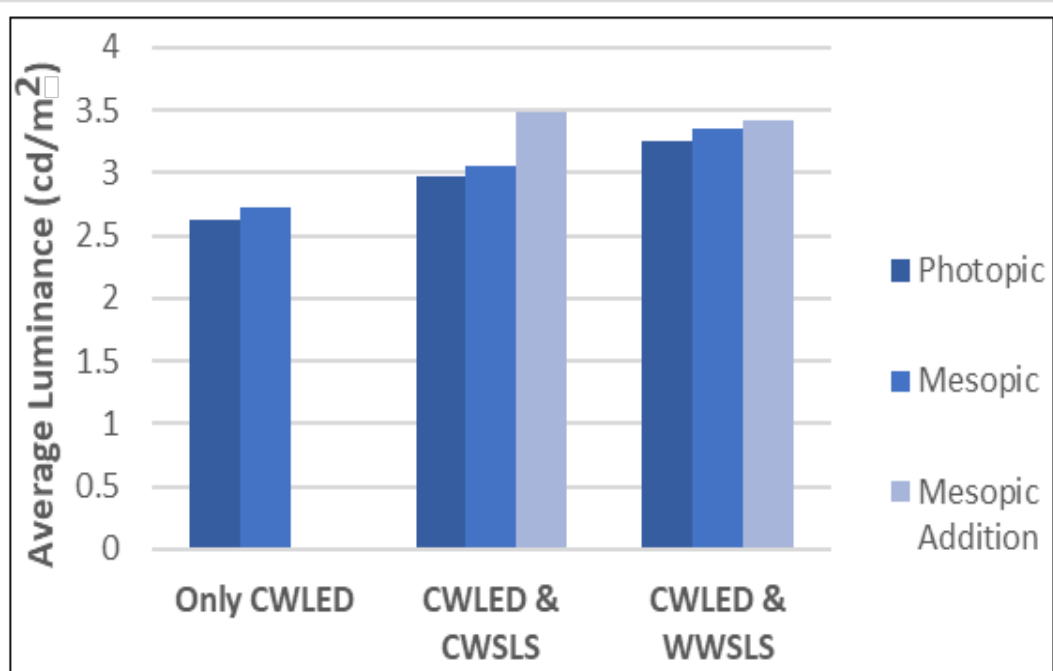


Fig. 5.9: Comparison of Photopic and Mesopic Luminance for CWLED

The above results show that:

- The combined mesopic luminance value is higher than the mesopic luminance when both light sources were lit together and the main light source and the surrounding light source both were cool white light source.
- When both the main light source and surrounding sources are of same S/P ratio, then the effective luminance will increase significantly.
- There is a slight difference between these two mesopic luminance when the main light source and surrounding light source were cool white and warm white respectively which indicate that when the main light source of any application area and surrounding sources are of opposite types of S/P ratio, then their effect will cancel each other and hence the effective luminance in both the cases

will remain same.

- The lamp with more blue content in its spectrum i.e. lamp with higher S/P ratio provides better performance in mesopic region. Although HPSV lamp shows better performance in photopic region but the effective luminance in mesopic region of MH and CWLED is higher than HPSV.
- In case of outdoor lighting due to presence of any surrounding sources with different spectrum characteristics, lamp performances with respect to effective luminance change significantly on the application field. Presence of light source of different S/P ratio than that of main source shows opposite performance than main light source.
- Among all the combinations, CWLED lamp with CWSLS sources shows best performance as effective luminance in mesopic region increases significantly, causing it more efficient lighting options.

5.4 Surrounding Luminance Effect on Adaptation Luminance

As discussed in **chapter 3**, the determination of adaptation luminance, luminous intensity distribution data of MLS and SLS are considered. Point specific illuminance values are computed from this intensity distribution data. The reflection factor of each grid point has been measured and considered as input in the computational programme. Then the photopic, mesopic and adaptation luminance of each grid point is calculated using the equations and block diagram as shown previously. The entire process is repeated for all the four types of lamps to understand their effectiveness when human eye is subjected to mesopic vision during night time for various lighting applications. The complete flow diagram is shown in **Fig. 5.10**.

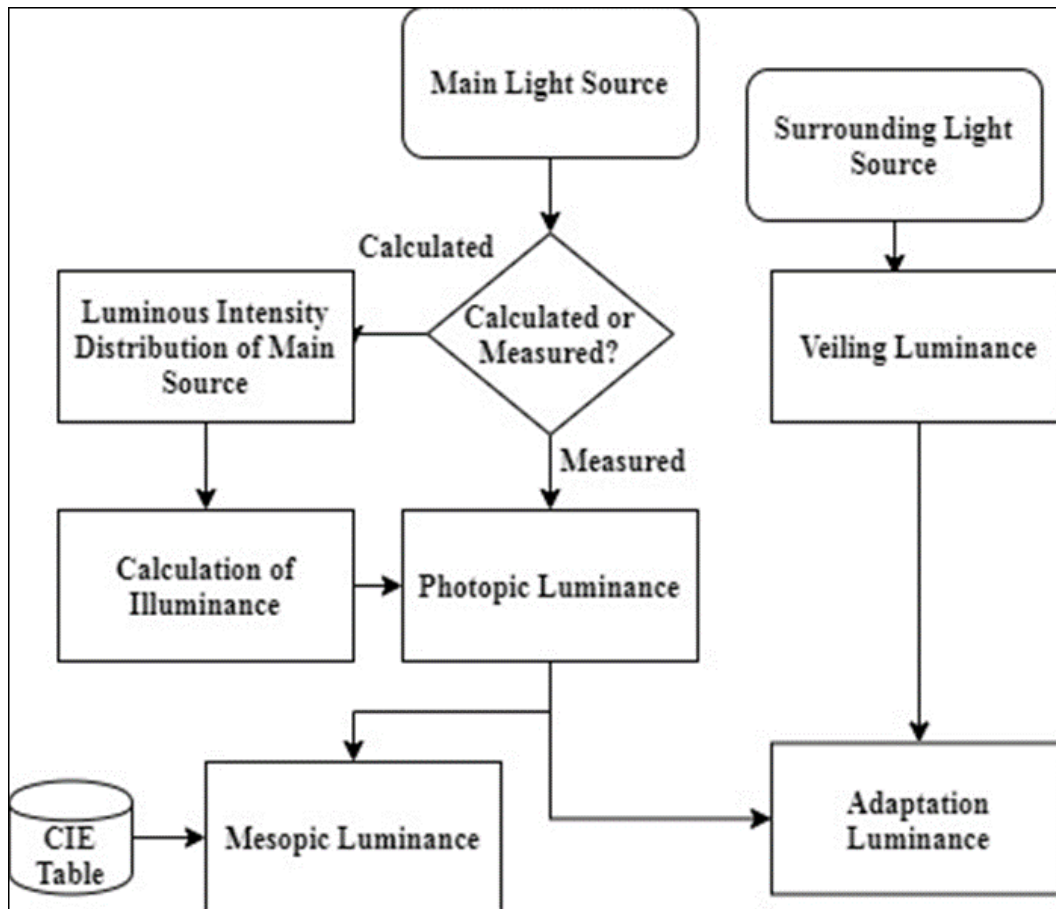


Fig. 5.10: Luminance Computational Flow Diagram

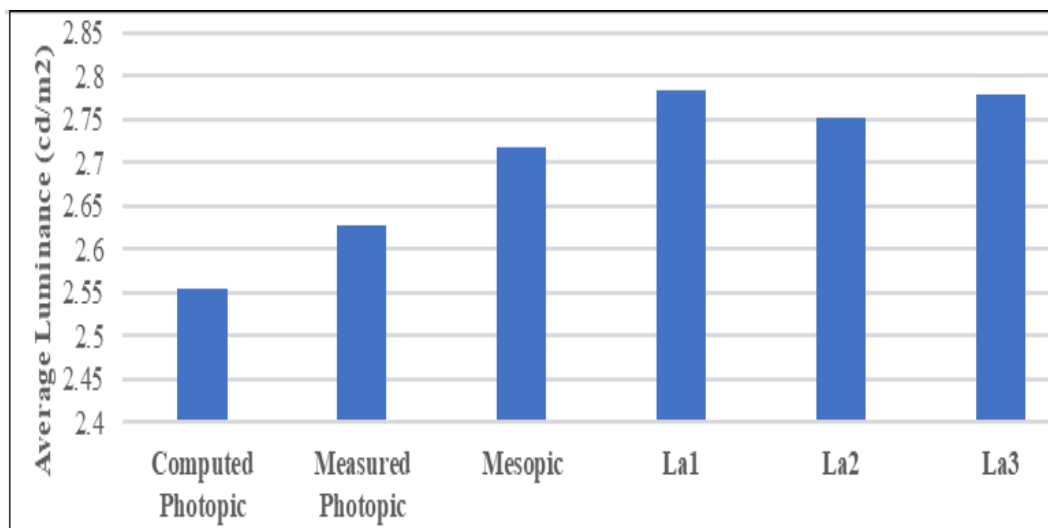


Fig. 5.11: Adaptation Luminance for WLED and CWLS

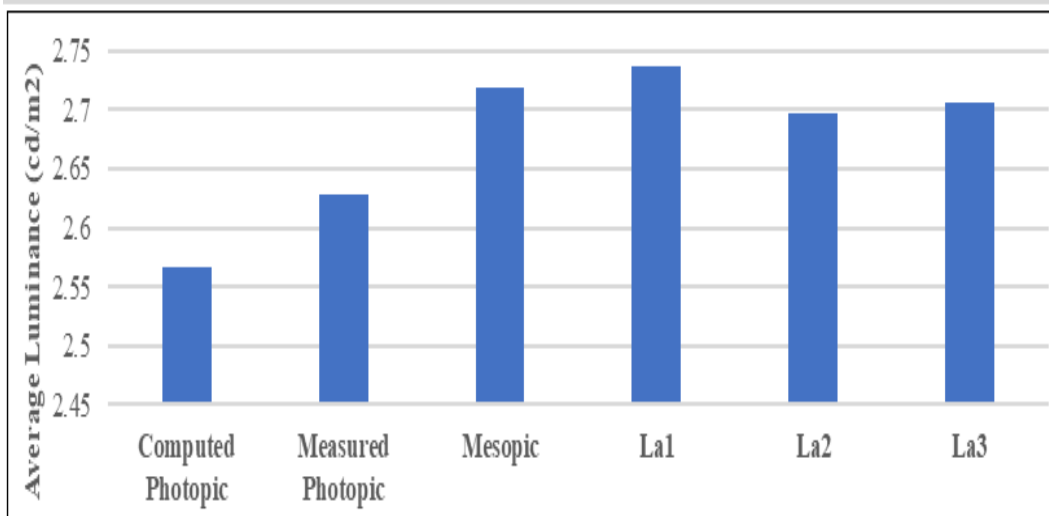


Fig. 5.12: Adaptation Luminance for WLED and WWSLs

Now comparison of adaptation luminance under two different surrounding lighting conditions has been shown in **Fig. 5.11** and **Fig. 5.12**. Here, the three adaptation luminance values i.e. L_{a1} , L_{a2} , L_{a3} are simulated from three veiling luminance models i.e. Uchida and Ohno model, Fry model and CIE general disability glare equation model respectively as described in **section 3.5.2**. As the CIE method is followed internationally, among the three adaptation luminance, the adaptation luminance which is calculated according to the CIE method (i.e. L_{a3}) is considered henceforth as adaptation luminance. One such sample computed values are shown in **Fig. 5.11** and **Fig. 5.12** for CWLED as MLS.

For the first case, increments in adaptation luminance were calculated by adding veiling luminance for three models and the percentage deviations were 5.92%, 4.69% and 5.75% respectively as shown in **Fig.5.11**. For the second set, increments in adaptation luminance were 4.14%, 2.59% and 2.96% respectively as shown in **Fig.5.12**. Therefore, these results clearly indicate that calculated adaptation luminance is almost same for all the three models.

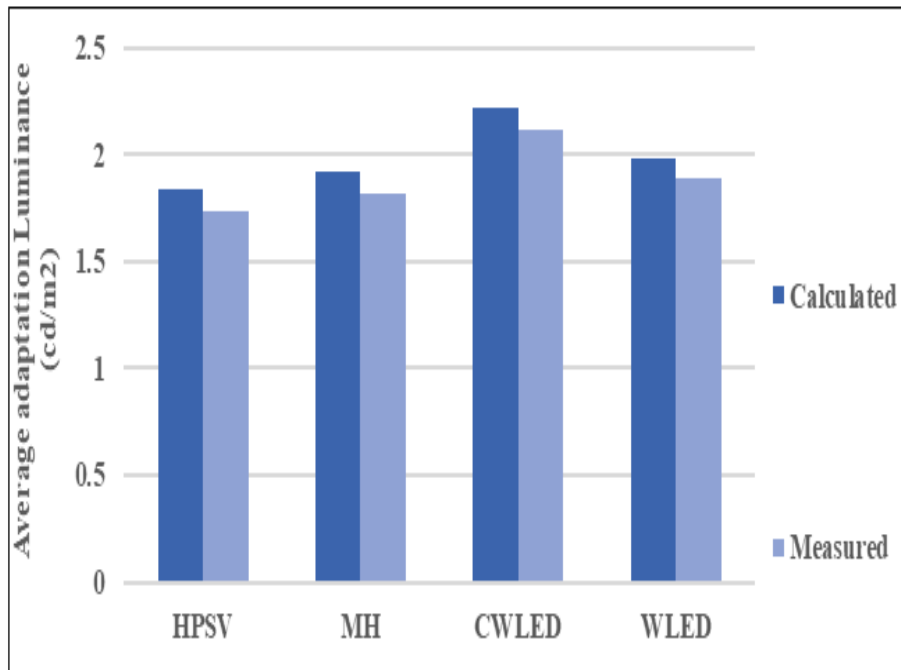


Fig. 5.13: Comparison of average adaptation luminance with MLS and CWSLS

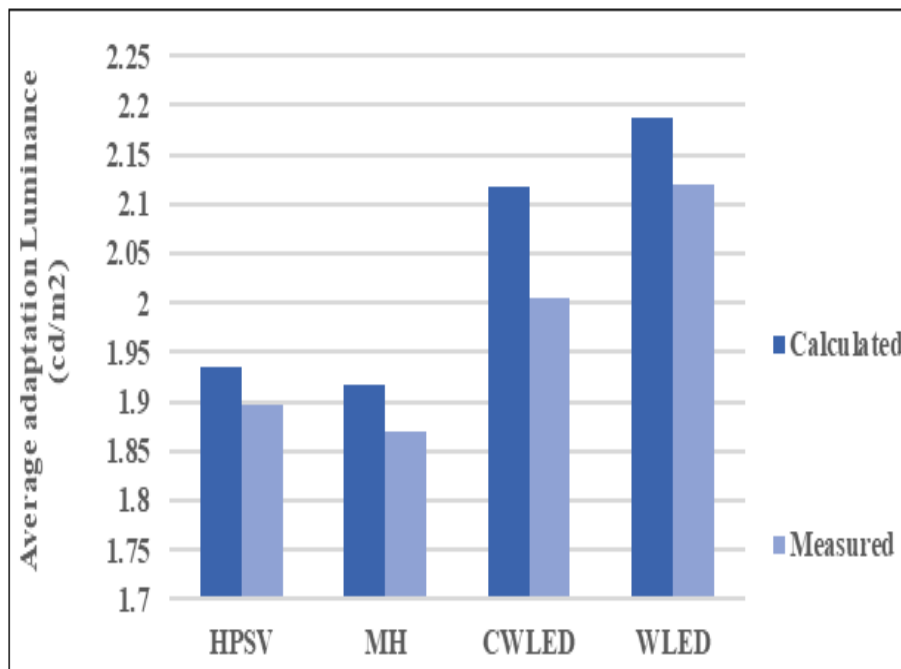


Fig. 5.14: Comparison of average adaptation luminance with MLS and WWSLS

Point specific adaptation luminance values are computed for presence of two different types of surrounding lighting ambience. The average values are shown in **Fig.5.13** and **Fig.5.14** for the cool white surrounding light source (CWSLS) and warm white surrounding light source (WWSLS) respectively. From above figures it can be observed that adaptation luminance of HPSV with WWSLS is greater than adaptation luminance of HPSV with CWSLS because S/P ratio of HPSV is very low, but due to effect of CWSLS, which has S/P ratio higher than warm SLS the adaptation luminance increases. So effect of a surrounding lamp with high S/P ratio on a particular application area is significant in mesopic field of vision. The adaptation luminance of CWLED with CWSLS is greater than adaptation luminance of CWLED with WWSLS because S/P ratio of CWLED is higher but due to effect of WWSLS, the adaptation luminance decreases. So effect of surrounding lamp on a particular application area has significant role in adaptation luminance which contributes to energy efficient mesopic design.

Fig.5.15 shows the percentage change in adaptation luminance for four lamps in two different surrounding lighting conditions. From the figure it is observed that in presence of surrounding light sources with same or comparable S/P ratio with the main light source, adaptation luminance get increased otherwise decreased. For example in case of HPSV lamp the average adaptation luminance is higher in case of warm white SLE than that of cool white SLE. The same results can be observed in case of MH, WLED & CWLED lamps. In case of these three lamps the value gets increased in cool white SLE over warm white SLE.



Fig. 5.15: Percentage change in adaptation luminance

5.4.1 Variation of adaptation luminance with surrounding source position

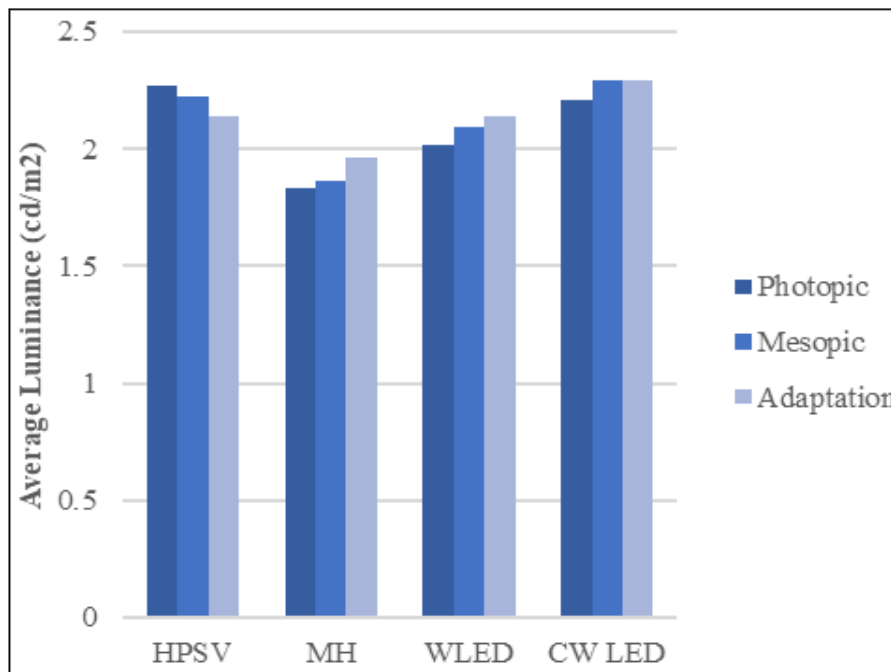


Fig. 5.16: Comparison of average luminance for MLS and CWSLS

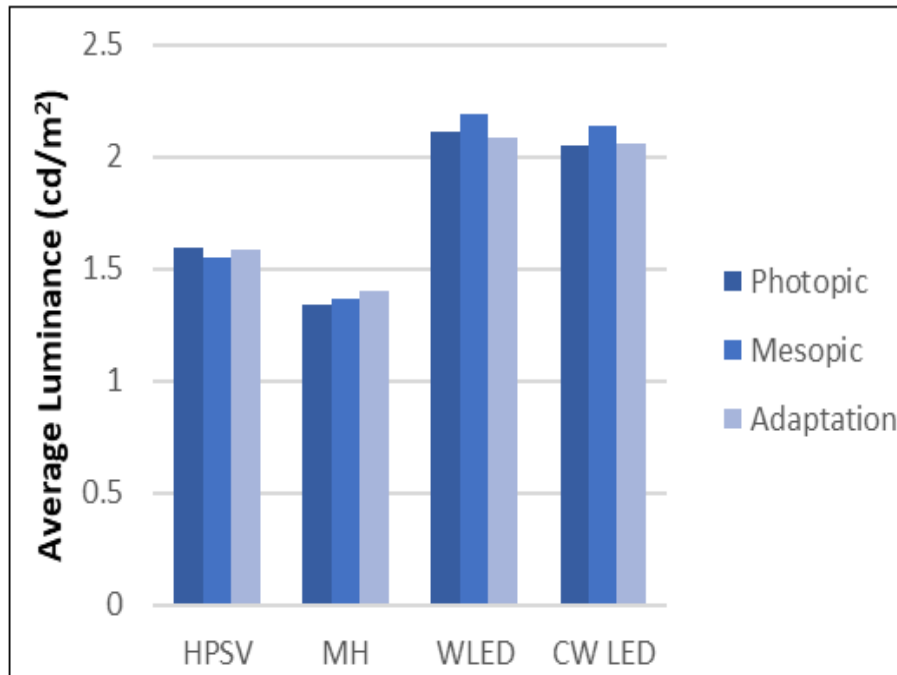


Fig. 5.17: Comparison of average luminance for MLS and WWSLS

The change in the adaptation state of the observer with respect to the position of surrounding sources within the field of view is also studied here. There are three different surrounding sources at three different positions. Comparison of average adaptation luminance for different surrounding light source positions has been shown in **Fig.5.18**. Here it is observed that among three surrounding light sources average adaptation luminance is maximum for SLS 2 which is nearest to the main light source. This finding suggests that the proximity of the surrounding light source to the main light source plays a significant role in determining the average adaptation luminance. Additionally, it indicates that the impact of the surrounding light source located at far from the MLS on adaptation luminance is minimal compared to the other sources.

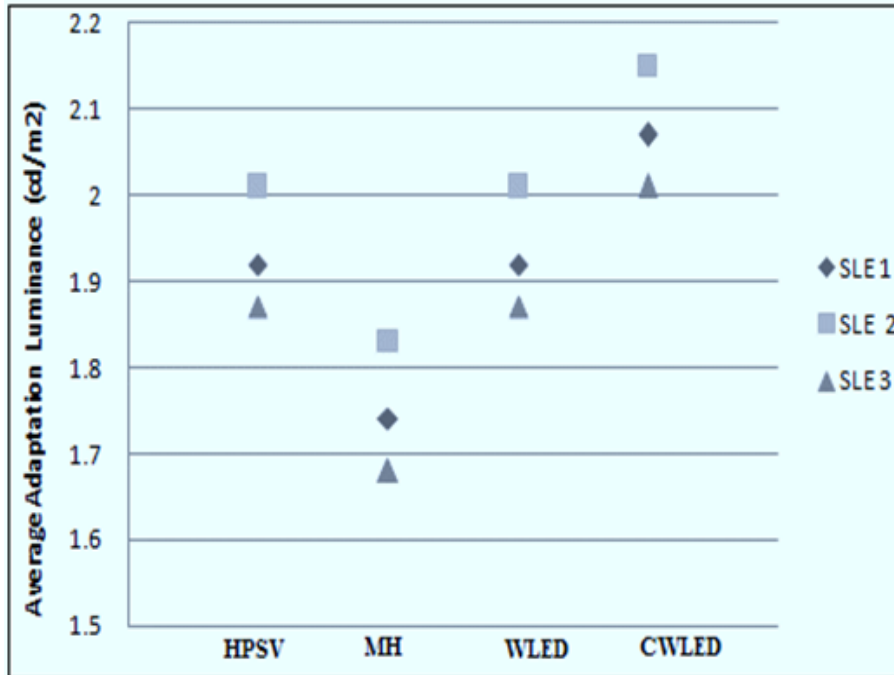


Fig. 5.18: Variation of adaptation luminance with surrounding source position

5.5 Comparative Analysis of Photopic, Mesopic and Adaptation Luminance

Comparison of average photopic, mesopic and adaptation luminance of the adaptation field and the adaptation state are shown below in **Fig.5.16** for cool white surrounding lighting condition and **Fig.5.17** for warm white surrounding lighting conditions. Here it is observed that the adaptation mesopic luminance is maximum and matching with mesopic luminance when both the main and surrounding sources have same or comparable spectrum characteristics.

In case of HPSV with CWFTL both mesopic and photopic luminance are greater than adaptation luminance because S/P ratio of HPSV is low. So human eye perceives less brightness. As the S/P ratio of HPSV lamp is not matching with both SLE, so effective luminance of field decreases in mesopic zone hence these lamps are not recommended for energy efficient mesopic design. In case of MH lamp,

the S/P ratio of MH is not matching with WWSLS and the effective luminance decreases but matching with CWSLS and hence effective luminance increases in field of mesopic vision. It can also be concluded that matching of S/P ratio of main and SLS sources has significant role on adaptation luminance. As in case of CWLED, S/P ratio of both main and CWSLS are matching and greater than 1, the effective luminance increases in mesopic field of vision. This combination (CWLED and CWFTL) will provide energy efficient performance in mesopic zones as spectral characteristics (blue content) of both main and SLE are same. For WLED the S/P ratio of WLED is matching with CWSLE so effective luminance increases but S/P ratio of WWFTL is less than WLED and hence effective luminance decreases in mesopic vision. CWLED and CWFTL with high S/P ratio gives more brightness with low wattage consumption leading to energy efficient lighting.

All the experimental data are considered and percentage change in adaptation luminance is shown in **Fig.5.19** for two extreme cases and for two types of MLS (i.e. HPSV & WLED) of different S/P ratio. It indicates that change in adaptation luminance due to presence of surrounding sources of different spectral characteristics. From the figure it is observed that maximum effective luminance can be achieved in case of WLED sources with cool surrounding lighting conditions. Change in adaptation luminance in case of WLED and surrounding light source of cool FTL is 5.456% and for warm FTL surrounding light source it is 3.236%.

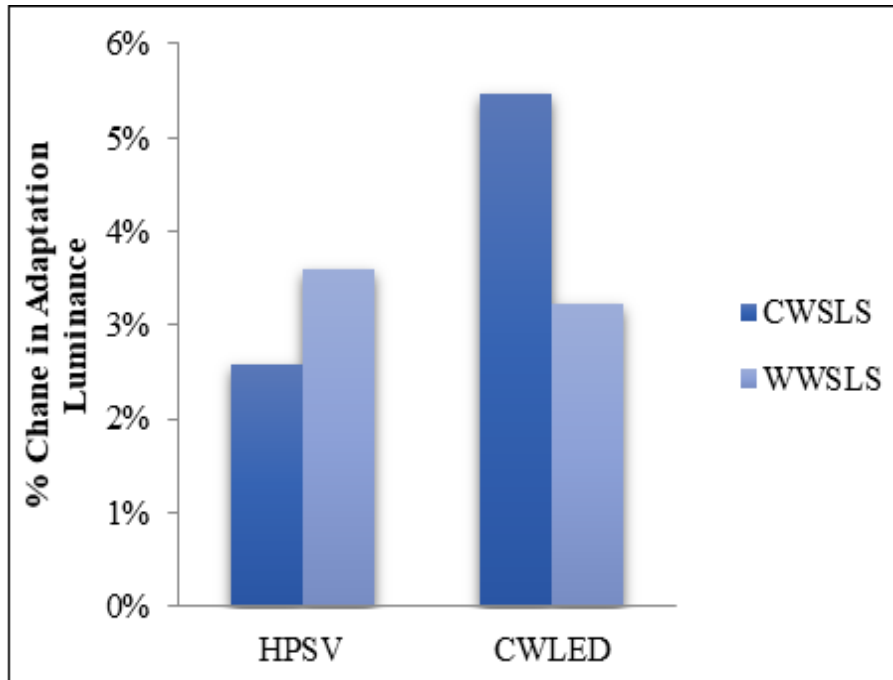


Fig. 5.19: Change in adaptation Luminance for different SLS and HPSV and CWLED as MLS

- **Computation using Source Spectral Power Distribution method**

In this method, the SPD of reflected light is the same as the SPD of the lamps used. These SPD methods can evaluate the mesopic quantities without S/P luminance meters [22]. The photopic luminance and the corresponding S/P ratio of the main lamp determine the adaptation coefficient (m). Corresponding adaptation luminance (considering the effects of surrounding lighting ambience) has been determined using the same method described earlier in **chapter 3 and 4**. This procedure is carried out for a single main lamp and two different surrounding lighting environments of cool and white lighting separately.

In **Fig.5.20**, average photopic, mesopic and adaptation luminance are shown when HPSV has been used as main light source. From the figure it is clear that due to low S/P ratio of HPSV (i.e. 0.48, less blue

wavelength emission in its SPD), adaptation coefficient m is in the lower range causing lower L_{mes} than L_p in the mesopic zone. Presence of cool surrounding light further reduces the adaptation state causing lower L_a value. However, presence of warm surrounding lighting increases the adaptation state, hence higher value of L_a .

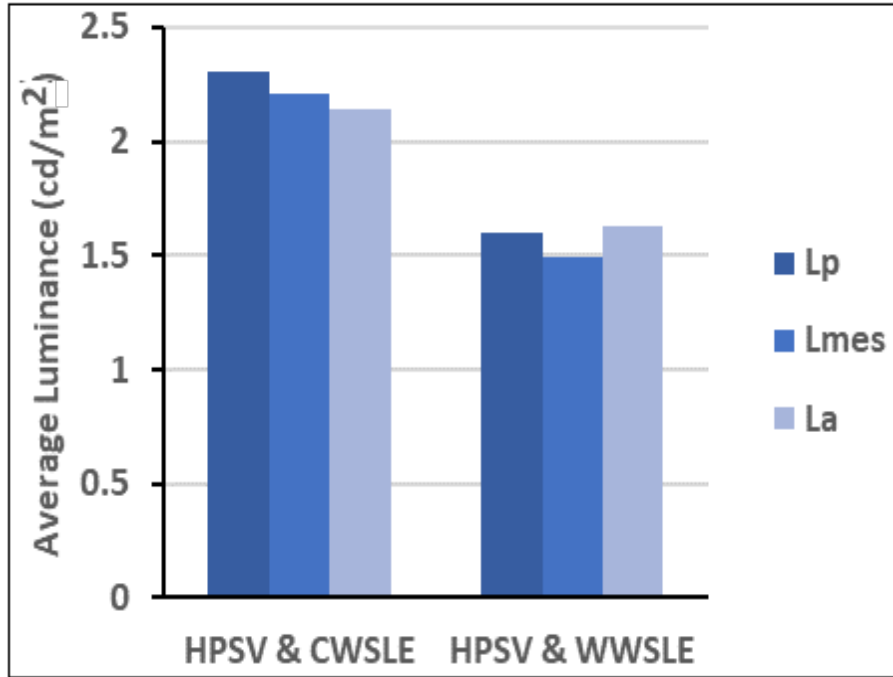


Fig. 5.20: Comparison of Average Luminance for HPSV

The above explanation is equally applicable for the three other main lamps i.e. MH, WLED, CWLED. From **Fig.5.21** it is clear that mesopic luminance is higher than the photopic luminance due to higher adaptation state in the presence of blue-enriched white light with more blue emission in the spectrum of MH lamp. Adaptation luminance to the eye of the observer is higher in the presence of cool surrounding lighting ambiance.

Similarly, when WLED has been used as main source, mesopic luminance is higher than photopic luminance due to higher S/P ratio. However, the adaptation luminance to the eye of the observer increases only when both the main light source and the surrounding source have

similar type of spectrum as shown in **Fig.5.22**.

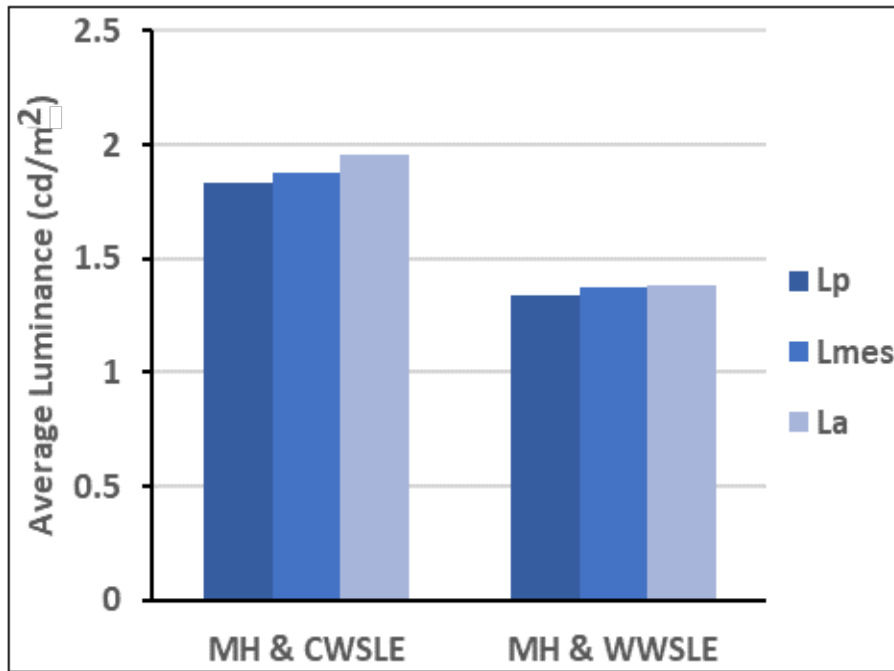


Fig. 5.21: Comparison of Average Luminance for MH

Due to a lamp of higher S/P ratio, CWLED showed significantly higher Lmes than Lp. Presence of warm white surrounding source which has less yellow content in its spectrum unlike CWLED source, effective luminance is almost same as measured photopic luminance. But effective adaptation luminance of the field increases significantly when both the main light source and surrounding lighting ambience consists of similar nature of spectrum as shown in **Fig.5.23**.

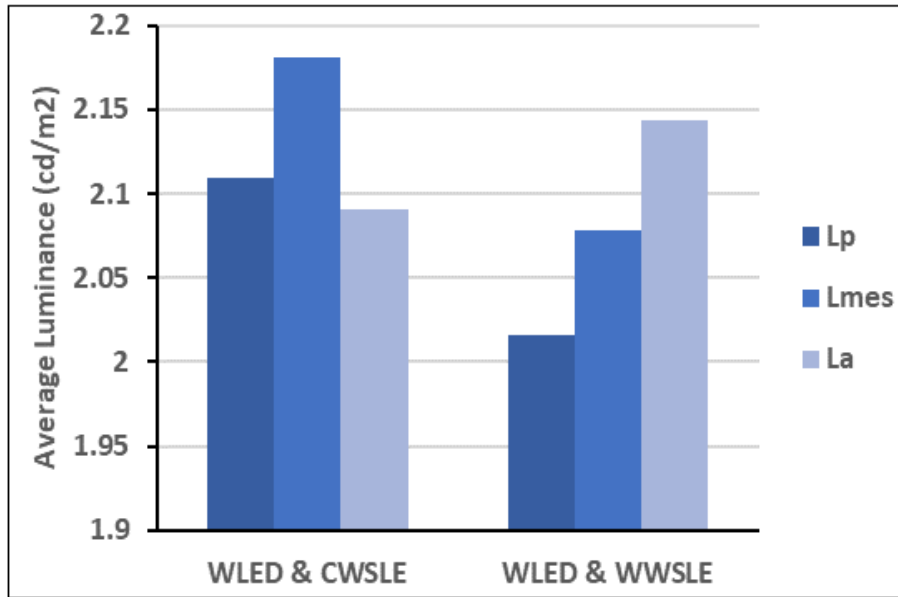


Fig. 5.22: Comparison of Average Luminance for WLED

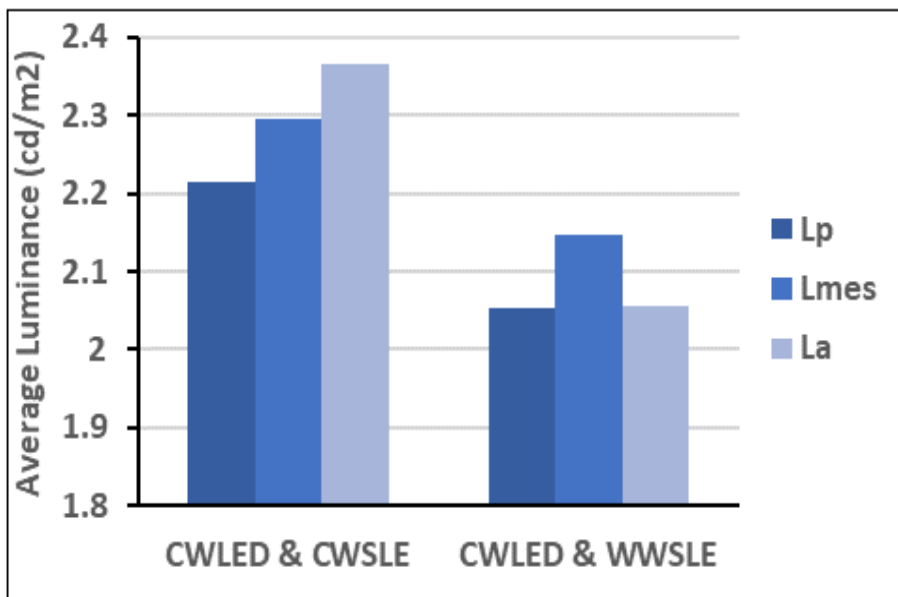


Fig. 5.23: Comparison of Average Luminance for CWLED

- **Effect of Surrounding Lighting Ambience**

From the above discussion it is clear that presence of various surrounding lighting ambience affect the adaptation state of the observer in different way. Considering the main conventional lamp i.e. HPSV

as the baseline, the changes in corresponding adaptation luminance with respect to that of HPSV are shown in **Fig.5.24** and **Fig.5.25** below.

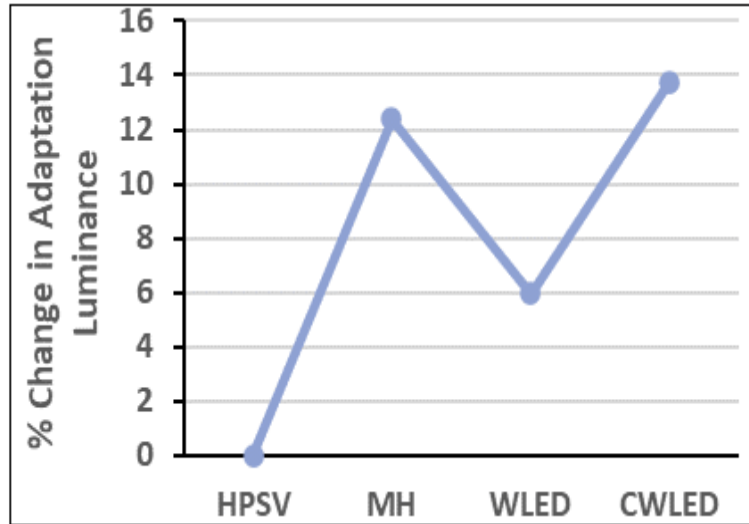


Fig. 5.24: Change in Adaptation luminance with respect to HPSV for CWSLS

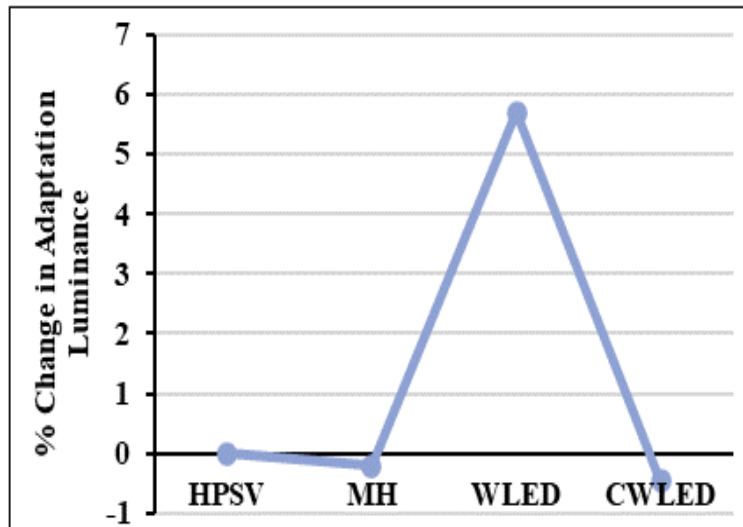


Fig. 5.25: Change in Adaptation luminance with respect to HPSV for WWSLS

From **Fig.5.24** it can be stated that effective luminance to the eye of the observer will increase significantly when the main and sur-

rounding lighting SPD are similar in nature. Here for two combinations i.e. for MH & CWLED lamps, increase in effective adaptation mesopic luminance is maximum. Again, in case of **Fig.5.25** there is negative change for these two combinations. Adaptation luminance increases in case of HPSV & WLED sources with WWSLE combinations. Therefore, it can be concluded that in case of outdoor lighting, where surrounding sources are present within the field of view of the observer along with the main light source, effective light to the eye of the observer increases significantly if both the lamps have similar type of emission in their corresponding spectrum. Among all the combinations CWLED shows best performance in presence of cool white surrounding ambience.

5.6 Chapter Summary

The objectives of this analysis were to study the adaptation luminance on the basis of peripheral adaptation of observers for implementation of mesopic photometry system in outdoor lighting and evaluation of performance of light sources with different spectral compositions under mesopic dimensioning. Here experimental procedure and simulation method have been employed to find out adaptation luminance. Following observations can be made based on the analysis of the experimental and simulation results:

- The nature of variation of adaptation luminance from photopic luminance is same as in case of mesopic luminance as per CIE standard method. Therefore, adaptation luminance can be considered instead of mesopic luminance for the fixed area of measurement (AOM).
- Adaptation luminance increases when surrounding veiling luminance sources are of same or comparable S/P ratio with the main light source in that application area. On the other hand, it decreases when S/P ratio of the surrounding light source is different from that of the main light source.
- Mesopic luminance and adaptation luminance are not same for the entire area of measurement (AOM) in presence of surrounding light sources. Mesopic luminance is more effective than adaptation luminance near the location of main light source than the surrounding areas. Therefore, in any field where veiling sources are present in line of sight, it is better to consider adaptation luminance over the mesopic luminance.
- Adaptation luminance also depends on the position of surrounding light source in the field of view. Effect of veiling luminance on

adaptation luminance changes with the distance of surrounding sources from both the main source and observer's position. Surrounding sources located near the main light source causes more deviation in adaptation luminance from mesopic luminance than the surrounding sources located far from the main light source.

The present experimental procedure can be utilized to evaluate the performance of different lamps and to identify the efficient lighting solutions applying mesopic photometry in appropriate lighting conditions.

• Publication

Studies and results discussed in Chapter 5 have been reported in the following publication:

Conference Publications: 2

1. Sangita Sahana, Jeenia Dey & Biswanath Roy. 2022. Energy Saving Potential of Lamps with Different Spectral Composition in Outdoor Lighting Applications under Mesopic Photometry System. **IEEE Calcutta Conference (CALCON)**, Kolkata, India, 2022, pp. 175-179, doi: 10.1109/CALCON56258.2022.10059863.

2. Sangita Sahana & Biswanath Roy. 2020. Estimation of Mesopic Adaptation Luminance under Different Surrounding Lighting Ambience. **IEEE Applied Signal Processing Conference (IEEE ASPCON)**, Kolkata, India, 2020, pp. 173-177, doi: 10.1109/ASPCON49795.2020.9276655.

6 Evaluation of Outdoor Lighting Design Based on Mesopic Dimensioning

In this chapter simulated photopic luminance, calculated mesopic luminance from CIE191:2010 and the computed mesopic luminance from DIALux 4.13 are compared for various lamps. The results show that CWLED lamps having the highest S/P ratio provide the most favorable mesopic design. Additionally, the simulated photopic luminance and calculated mesopic luminance align closely with the actual measurements of the CWLED lamps, confirming their effectiveness for mesopic applications.

6.1 Introduction

In the mesopic photometry system, it is crucial to consider the Scotopic/Photopic (S/P) ratio of a light source to calculate the mesopic luminance. A higher S/P ratio indicates that the light source is more effective for mesopic vision. This characteristic is particularly advantageous for road and many outdoor lighting applications, as it contributes to energy-efficient design. In practical terms, many white light sources have a higher S/P ratio, making them well-suited for road lighting design where energy efficiency is a key consideration. WLED technology has emerged as a promising solution in mesopic applications due to the presence of more blue light in its spectrum. In this chapter the adaptation luminance has been computed for a real scenario with two MLS and three SLSs together. DIALux 4.13 is a widely-used lighting design software that primarily relies on photometric values for its simulations and calculations. However, the transition from photopic to mesopic vision, especially in outdoor and transitional lighting scenarios, presents significant opportunities for improving lighting design efficiency and effectiveness. This work focuses on the transformation of the photopic luminous flux provided by the manufacturer to its equivalent mesopic luminous flux and simulation of average mesopic luminance values by using DIALux software and tries to study comparative analysis of simulated photopic luminance, calculated mesopic luminance from CIE191:2010 and simulated mesopic luminance of different lamps.

6.2 Visual Adaptation Luminance in Mesopic Photometry System For more than one MLS

The process described in **Chapter 3** for computation of adaptation luminance is followed here but another scenario. Here instead of one, two MLS have been used. So if the output remain same as before, it

will be possible to state the applicability of this model. Here the total area of measurement is divided into 66 grid points as before and shown in **Fig.6.1**. There are two same type of luminaires used as main light sources and three surrounding sources.

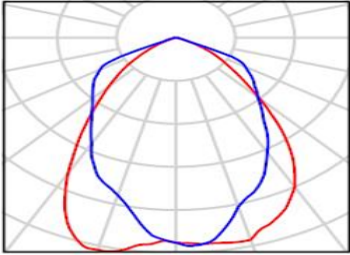
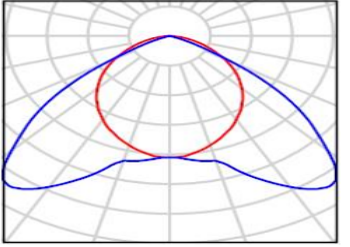
Name of Luminaire	Details of Fixture	Light Distribution Curve
PHILIPS SWF 101/150W [SYMMETRIC], CLOSED	<ul style="list-style-type: none"> • Luminous flux (Luminaire): 9856 <u>lm</u> • Luminous flux (Lamps): 14000 <u>lm</u> • Luminaire Wattage: 170 W • Luminaire classification according to CIE: 100 • CIE flux code: <u>62 91 99 100 70</u> • Fitting: 1 x SON T 150W (Correction Factor 1.000). 	
TCS 306 / 136 M1	<ul style="list-style-type: none"> • Luminous flux (Luminaire): 2261 <u>lm</u> • Luminous flux (Lamps): 3250 <u>lm</u> • Luminaire Wattage: 45.2 W • Luminaire classification according to CIE: 100 • CIE flux code: <u>49 87 98 100 70</u> • Fitting: 1 x TL'D'36W/865 (Correction Factor 1.000). 	

Fig. 6.1: Luminaires with Specification for HPSV and SLS

• Computation of Photopic Luminance

Photopic Luminance (L_p) values are calculated for all the grid points for three different types of main light sources i.e. HPSV, MH and CWLED lamps using MATLAB software. The coding is given in Appendix 1. Only the computed results for CWLED are shown here. All other data are provided in Appendix 6. The calculated illuminance values for CWLED as MLS are shown in **Table 6.1** and simulated Photopic luminance values are shown in the table **Table 6.2**.

The average value of simulated Photopic luminance (L_p) for all different lamps are shown in **Table 6.3**.

Table 6.1: Illuminance value for all grid points for CWLED as MLS

	A	B	C	D	E	F
1	21	19.2	16.2	13.4	11.8	9.2
2	21.5	19.7	16.3	13.4	11.4	8.6
3	22.2	19.9	16.8	13.6	10.6	7.8
4	22.5	20.1	16.9	13.4	10.2	7.4
5	21.6	19.5	16.2	12.7	9.6	7.0
6	22.1	19.8	16.5	12.8	9.4	6.8
7	21.6	19.5	16.2	12.8	9.6	7.02
8	22.5	20.1	16.9	13.4	10.2	7.4
9	22.2	19.9	16.7	13.6	10.6	7.8
10	21.5	19.7	16.3	13.4	11.4	8.5
11	21.1	19.2	16.2	13.4	11.7	9.2

Table 6.2: Simulated Photopic luminance (L_p) values in cd/m^2

	A	B	C	D	E	F
1	4.67	4.21	4.76	3.11	4.21	3.99
2	4.24	4.23	4.29	3.15	4.34	4.23
3	4.79	4.54	4.76	3.54	3.76	3.43
4	4.21	4.98	4.87	3.18	3.16	3.11
5	4.34	4.78	3.42	3.44	2.45	2.97
6	3.98	4.65	3.54	3.65	2.43	2.87
7	3.99	4.59	3.78	3.55	3.98	2.56
8	3.5	3.67	3.43	2.56	3.45	2.12
9	2.65	3.20	3.12	2.55	3.23	2.02
10	2.12	2.87	2.50	2.42	2.23	2.00
11	2.31	1.98	2.11	2.22	2.48	1.76

Table 6.3: Computed Photopic luminance (in cd/m^2) for all lamps

MLS	Average Photopic Luminance
HPSV	3.54
MH	2.32
CWLED	3.65

• Computation of Adaptation Luminance

In the previous chapters, the computation process of adaptation luminance (L_a) are discussed in detail. Here the same process has been repeated for two main light sources. In this section, the computed data for CWLED are given below. All other coding and data for other

types of lamps are shown in Appendix. For CWLED lamp adaptation luminance are simulated and shown in **Table 6.4**.

Table 6.4: Computed Adaptation luminance values (in cd/m^2)

	A	B	C	D	E	F
1	0.80	0.92	1.46	0.75	0.66	0.42
2	0.72	0.78	0.80	0.68	0.55	0.41
3	0.60	0.67	0.66	0.75	0.43	0.36
4	0.60	0.83	0.68	0.81	0.44	0.28
5	0.56	0.57	0.59	0.80	0.55	0.34
6	0.63	0.56	0.66	0.80	0.89	0.39
7	0.59	0.61	0.72	0.61	1.32	0.63
8	0.79	0.67	0.73	0.54	1.44	0.66
9	0.82	0.76	0.86	0.67	1.12	0.49
10	0.67	0.85	0.96	0.85	1.07	0.34
11	0.80	1.03	1.21	1.33	1.47	0.42

The computed adaptation Luminance (L_a) values for all different Lamps when all SLEs are on are shown in **Table 6.5**.

Table 6.5: Computed Adaptation luminance (in cd/m^2) for all MLSs with all SLSs

MLS	Average Photopic Luminance
HPSV	3.52
MH	2.89
CWLED	4.12

• Result Analysis

The photopic and adaptation luminance values are subjected to a comparative analysis, shedding light on the characteristics of the adaptation field within the mesopic photometry system. The comparison of average photopic Luminance and average adaptation Luminance for all the lamps are shown in **Fig.6.2**.

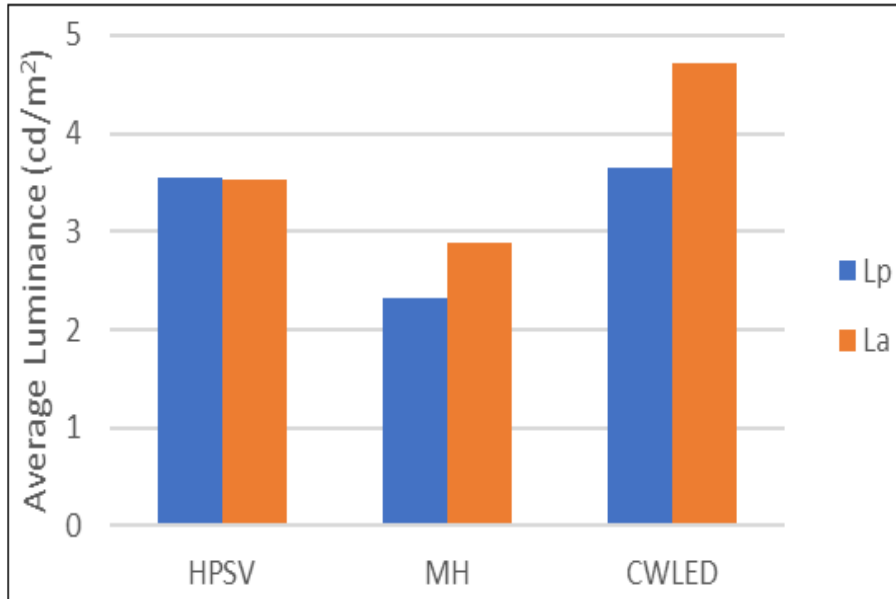


Fig. 6.2: Comparison of average Photopic and Adaptation Luminance

From the above figure it can be observed that the adaptation luminance increases significantly in presence of any surrounding source. The effect is more visible for the blue light enriched lamps also in presence of two main light sources. Hence they provide better performance in mesopic design. This statement follows the trend seen for single source also. Hence this model can be applied in more general form, i.e. the adaptation characteristics and performance of lamps can be determined in this way. Considering the energy perspective, Cool White LED (CWLED) lighting offers a more energy-efficient solution compared to Metal Halide (MH) lighting. It consumes less power while still providing a reasonable level of perceived brightness. This efficiency can lead to cost savings and reduced energy consumption, making CWLED lighting a preferred choice for outdoor lighting applications where energy efficiency is a key consideration.

6.3 Lighting Design in Photopic Region

In this section, lighting design of the mentioned area has been done with metal halide (MH), high pressure sodium vapour (HPSV) and cool white LED lamps using the DIALux lighting simulation software (Version 4.13) (created by the DIAL company). The goal of this section is to verify and validate the method described previously.

6.3.1 Lighting Design using HPSV as MLS

Here the same luminaire has been used for lighting design using DIALux 4.13.

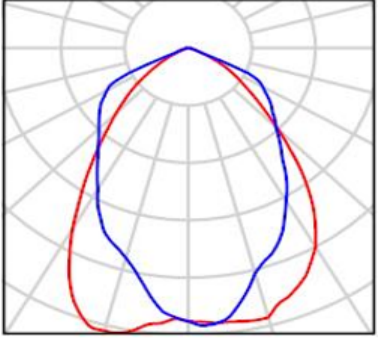
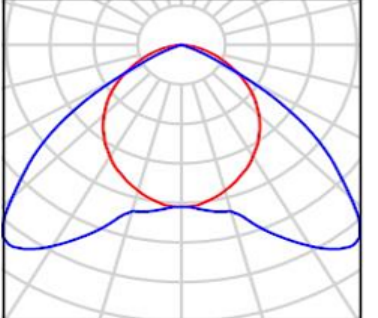
Name of Luminaire	Details of Fixture	Light Distribution Curve
PHILIPS SWF 101/150W [SYMMETRIC], CLOSED	<ul style="list-style-type: none"> • Luminous flux (Luminaire): 9856 <u>lm</u> • Luminous flux (Lamps): 14000 <u>lm</u> • Luminaire Wattage: 170 W • Luminaire classification according to CIE: 100 • CIE flux code: <u>62 91 99 100 70</u> • Fitting: 1 x SON T 150W (Correction Factor 1.000). 	
TCS 306 / 136 M1	<ul style="list-style-type: none"> • Luminous flux (Luminaire): 2261 <u>lm</u> • Luminous flux (Lamps): 3250 <u>lm</u> • Luminaire Wattage: 45.2 W • Luminaire classification according to CIE: 100 • CIE flux code: <u>49 87 98 100 70</u> • Fitting: 1 x TL'D'36W/865 (Correction Factor 1.000). 	

Fig. 6.3: Luminaires with Specification for HPSV

- **Luminaire Details**

The details of the lamps and luminaires used for the design have been given in **Fig.6.3**.

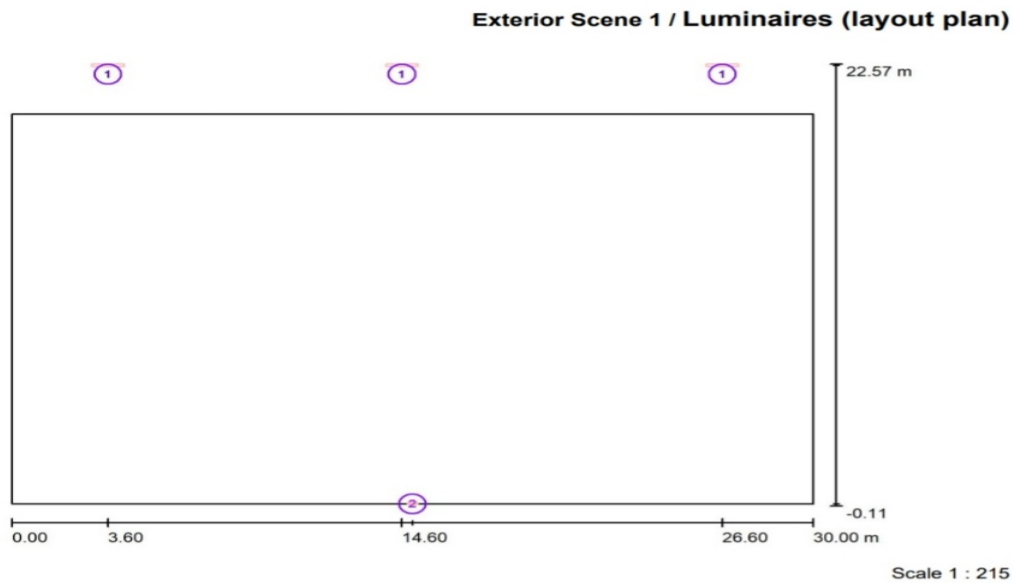
- **Design Considerations**

-Area of the space: 30*20m

-Luminaire used: 3 x PHILIPS SWF 101/150W [Symmetric], and 3 x TCS 306 / 136 M1(surrounding light source)

-Pole height : 9m

The layout of the designed area and luminaire coordinate list with the positions of the luminaire are shown in **Fig.6.4** and **Fig.6.5** respectively. Here two different type of lamps are used, one is fluorescent lamp (used as surrounding light source) denoted as 1 and the other one is high pressure sodium vapour lamp which is denoted as 2.



Luminaire Parts List

No.	Pieces	Designation
1	3	TCS 306 / 136 M1
2	3	PHILIPS SWF 101/150W [SYMMETRIC], CLOSED,

Fig. 6.4: Luminaires layout plan for HPSV

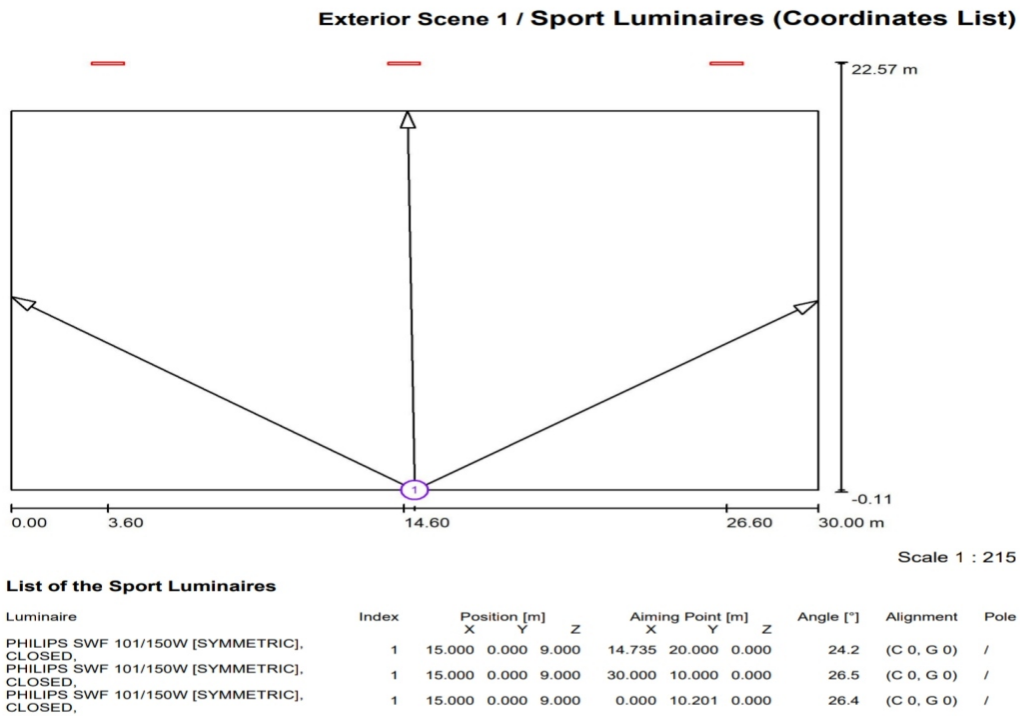


Fig. 6.5: Coordinates list of luminaires for HPSV

• Design Output

The iso-lux diagram for the area under measurement has been shown in **Fig.6.6**.

All the point-specific luminance values for the AOM have been shown in **Fig.6.7** from the DIALux design output. The corresponding average, maximum and minimum luminance values of the design area are given in the figure. The values obtained throughout the area are as follows:

- Average luminance (L_{avg}) = 1.69 cd/m².
- Overall Uniformity (U_0) = 0.265.

Exterior Scene 1 / Ground Element 1 / Surface 1 / Isolines (L)

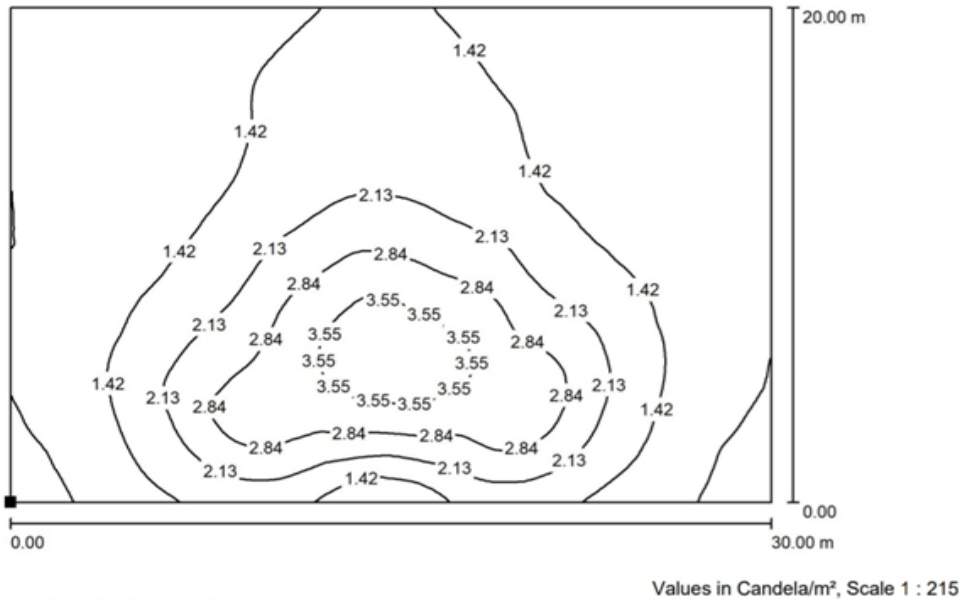


Fig. 6.6: Isolines diagram of the AOM for HPSV

Exterior Scene 1 / Ground Element 1 / Surface 1 / Value Chart (L)

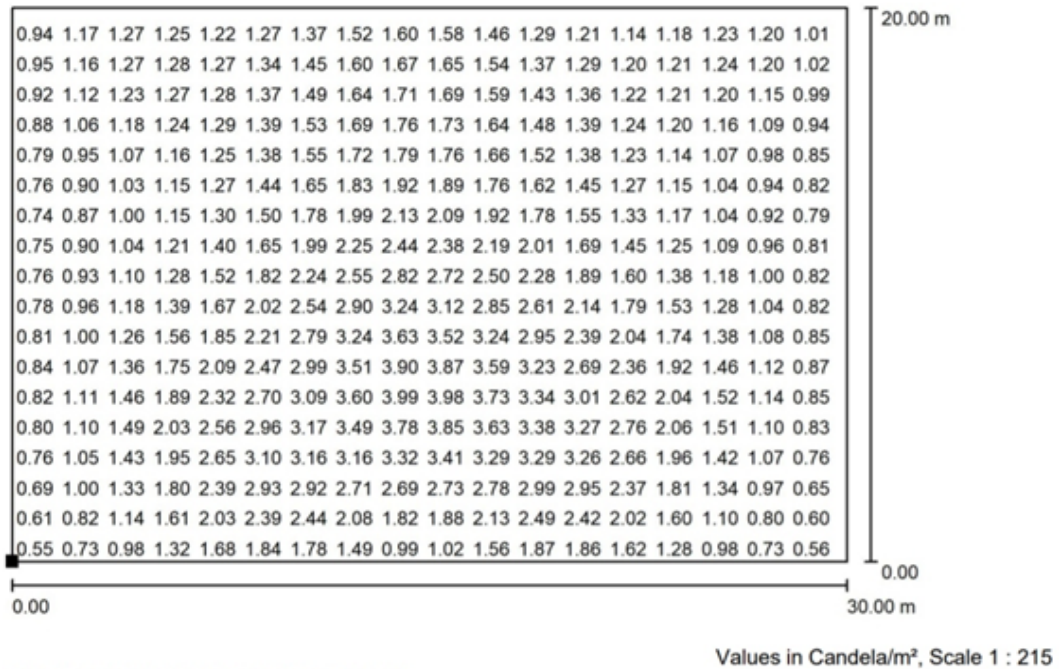


Fig. 6.7: Value chart of point specific photopic luminance for HPSV

6.3.2 Lighting Design using MH as MLS

Here the same luminaire has been used for lighting design using DI-ALux 4.13.

- **Luminaire Details**

The details of the lamps and luminaires used for the design have been given in **Fig.6.8**.

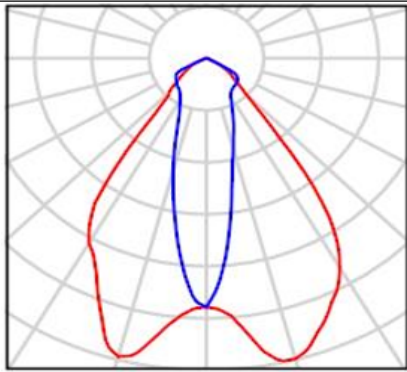
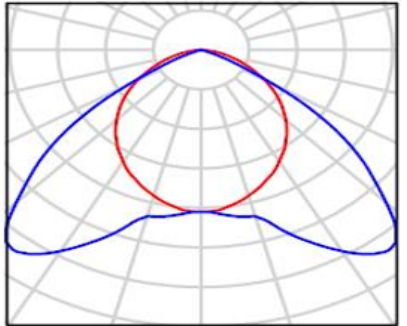
Name of Luminaire	Details of Fixture	Light Distribution Curve
PHILIPS MWF 101/150W [SYMMETRIC], CLOSED	<ul style="list-style-type: none"> • Luminous flux (Luminaire): 8627 <u>lm</u> • Luminous flux (Lamps): 12100 <u>lm</u> • Luminaire Wattage: 170W • Luminaire classification according to CIE: 100 • CIE flux code: <u>71 93 99 100 71</u> • Fitting: 1 x MHN TD 150W (Correction Factor 1.000). 	
TCS 306 / 136 M1	<ul style="list-style-type: none"> • Luminous flux (Luminaire): 2261 <u>lm</u> • Luminous flux (Lamps): 3250 <u>lm</u> • Luminaire Wattage: 45.2 W • Luminaire classification according to CIE: 100 • CIE flux code: <u>49 87 98 100 70</u> • Fitting: 1 x TL'D'36W/865 (Correction Factor 1.000). 	

Fig. 6.8: Luminaires with Specification for MH

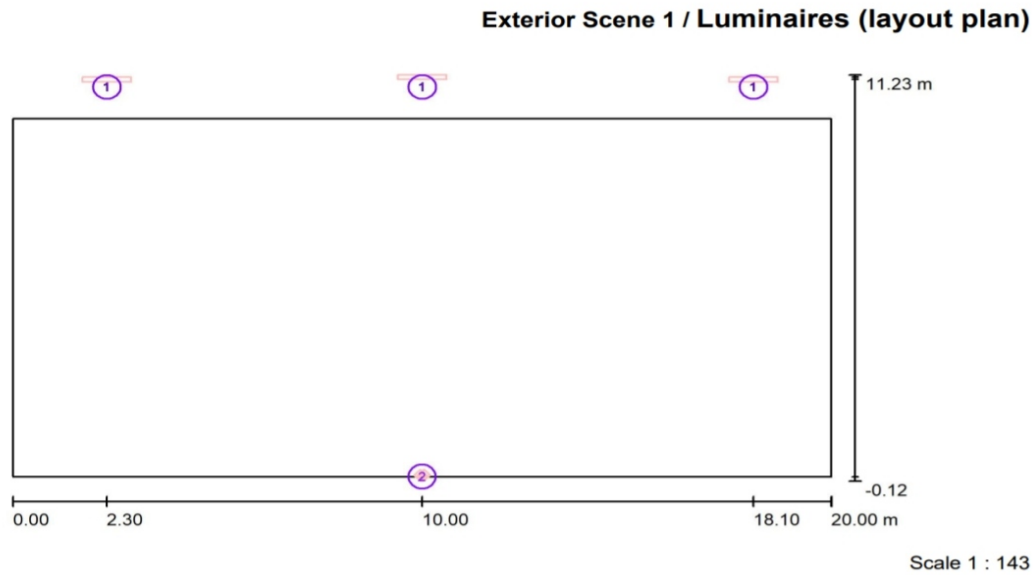
- **Design Considerations**

-Area of the space: 20*10m

-Luminaire used: 2 x PHILIPS MWF 101/150W [Symmetric], CLOSED and 3 x TCS 306 / 136 M1(surrounding light source)

-Pole height : 9m

In **Fig.6.9** the layout of the design area and the positions of the luminaires are shown. Here again the fluorescent lamp i.e, surrounding light source and Metal Halide i.e MLS have been denoted as 1 and 2 respectively. Luminaire coordinate list has been shown in **Fig.6.10**.



Luminaire Parts List

No.	Pieces	Designation
1	3	TCS 306 / 136 M1
2	2	PHILIPS MWF 101/150W [SYMMETRIC], CLOSED,

Fig. 6.9: Luminaires layout plan for MH

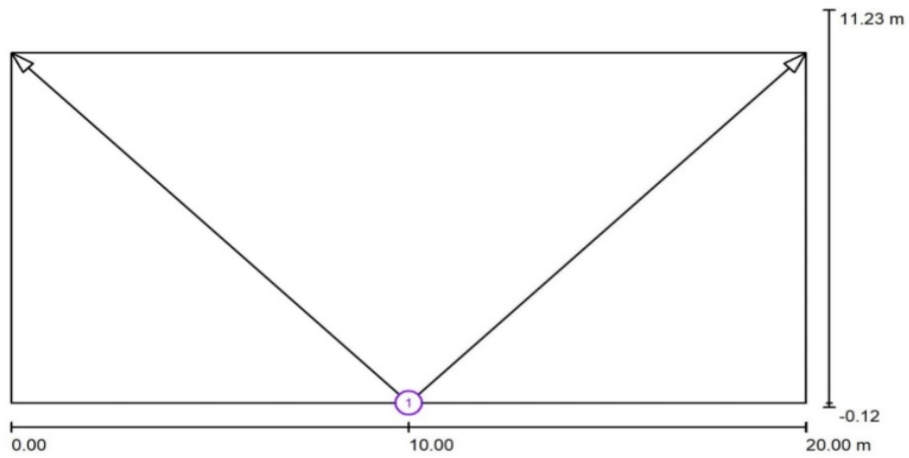
• **Design Output**

The iso-lux diagram for the area under measurement has been shown in **Fig.6.11**. All the point-specific luminance values for the AOM have been shown in **Fig.6.12** from the DIALux design output. The corresponding average, maximum and minimum luminance values of the design area are given in the figure. The values obtained throughout the area are as follows:

-Average luminance (L_{avg}) = 3.86 cd/m².

-Overall Uniformity (U_0) = 0.347.

Exterior Scene 1 / Sport Luminaires (Coordinates List)



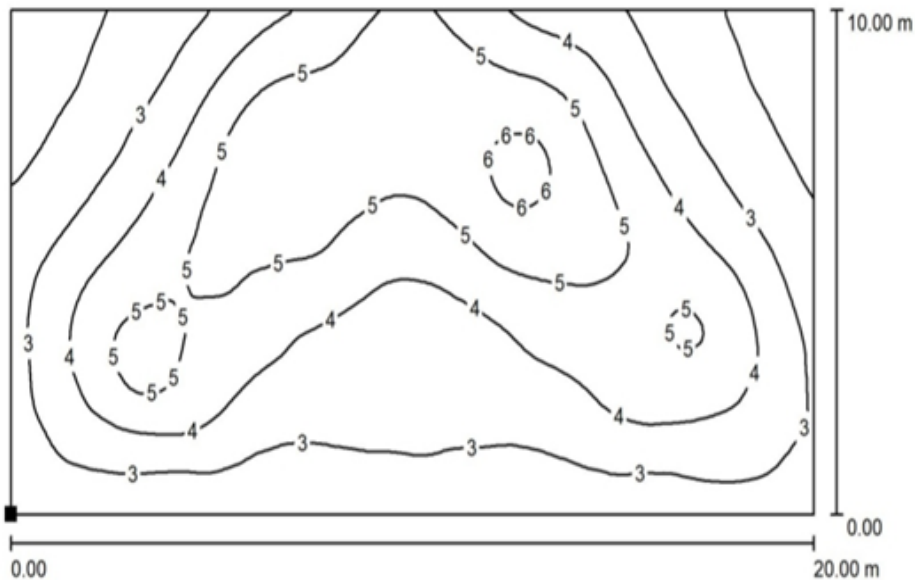
Scale 1 : 143

List of the Sport Luminaires

Luminaire	Index	Position [m]			Aiming Point [m]			Angle [°]	Alignment	Pole
		X	Y	Z	X	Y	Z			
PHILIPS MWF 101/150W [SYMMETRIC], CLOSED,	1	10.000	0.000	9.000	0.000	10.000	0.000	32.5	(C 90, G IMax)	/
PHILIPS MWF 101/150W [SYMMETRIC], CLOSED,	1	10.000	0.000	9.000	20.000	10.000	0.000	32.5	(C 90, G IMax)	/

Fig. 6.10: Coordinates list of luminaires for MH

Exterior Scene 1 / Ground Element 1 / Surface 1 / Isolines (L)



Values in Candela/m², Scale 1 : 143

Fig. 6.11: Isolines diagram of the AOM for MH

Exterior Scene 1 / Ground Element 1 / Surface 1 / Value Chart (L)

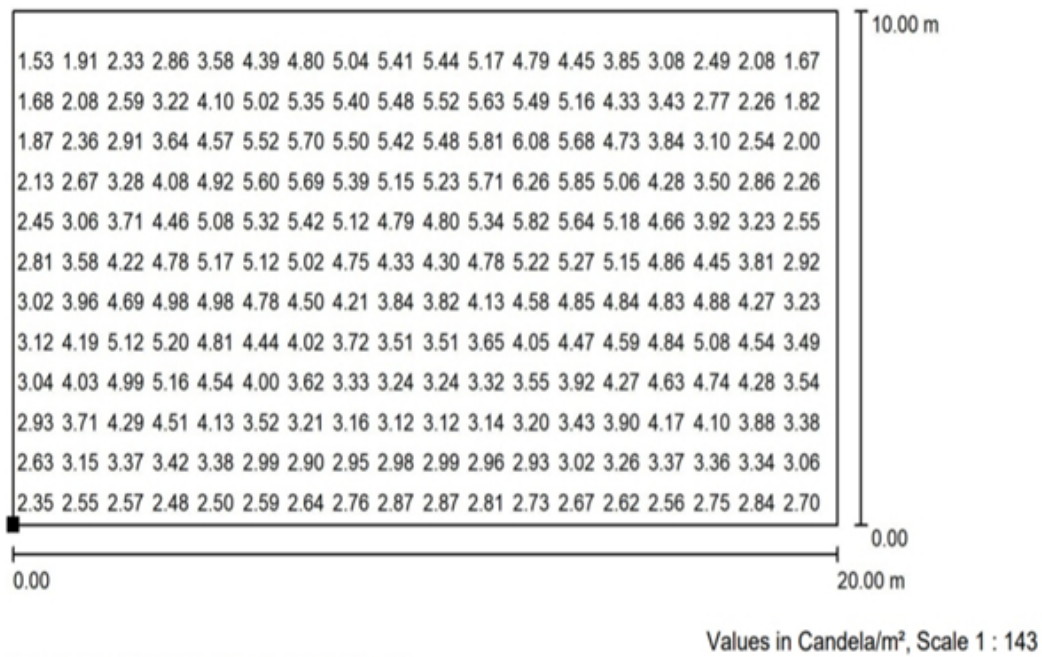


Fig. 6.12: Value chart of point specific photopic luminance for MH

6.3.3 Lighting Design using CWLED as MLS

Here the same luminaire has been used for lighting design using DI-ALux 4.13.

- **Luminaire Details**

The details of the lamps and luminaires used for the design have been given in **Fig.6.13**.

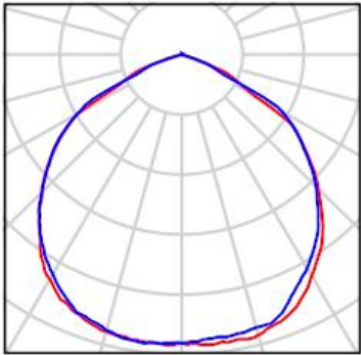
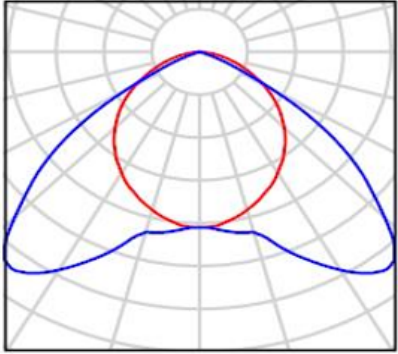
Name of Luminaire	Details of Fixture	Light Distribution Curve
Orbit Industries, Inc.	<ul style="list-style-type: none"> • Luminous flux (Luminaire): 14498 lm • Luminous flux (Lamps): 14499 lm • Luminaire Wattage: 158.6 W • Luminaire classification according to CIE: 100 • CIE flux code: 54 89 100 100 100 • Fitting: 1 x LFL4-160W (Correction Factor 1.000). 	
TCS 306 / 136 M1	<ul style="list-style-type: none"> • Luminous flux (Luminaire): 2261 lm • Luminous flux (Lamps): 3250 lm • Luminaire Wattage: 45.2 W • Luminaire classification according to CIE: 100 • CIE flux code: 49 87 98 100 70 • Fitting: 1 x TL'D'36W/865 (Correction Factor 1.000). 	

Fig. 6.13: Luminaires with Specification for CWLED

- **Design Considerations**

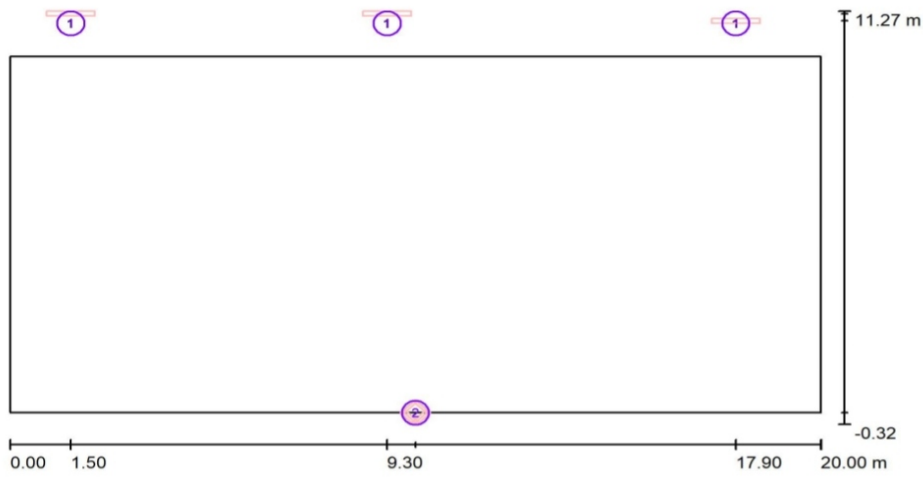
-Area of the space: 20*10m

-Luminaire used: 1 x LFL4-160W [Symmetric], CLOSED and 3 x TCS 306 / 136 M1(surrounding light source)

-Pole height : 9m

The layout of the designed area and luminaire coordinate list with the positions of the luminaire are shown in **Fig.6.14** and **Fig.6.15** respectively. Here again the MLS has been denoted as 2 and SLSs have been denoted as 1.

Exterior Scene 1 / Luminaires (layout plan)



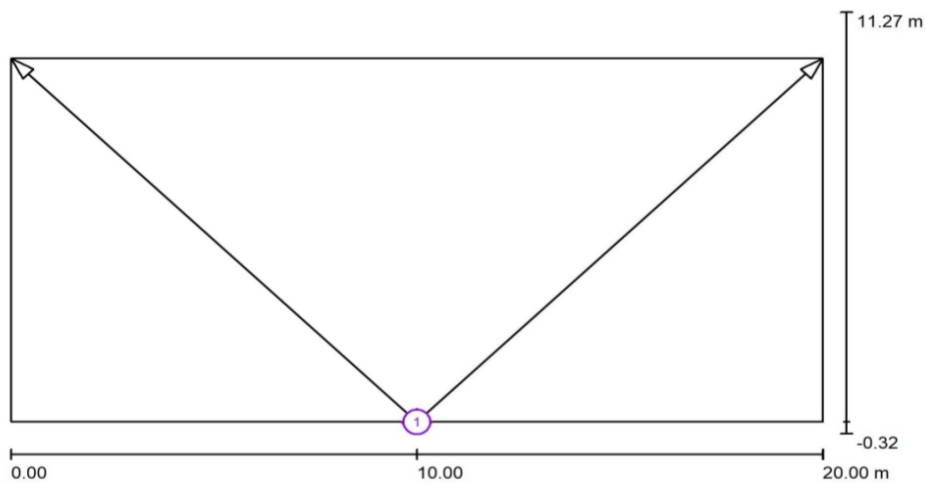
Scale 1 : 143

Luminaire Parts List

No.	Pieces	Designation
1	3	TCS 306 / 136 M1
2	2	Orbit Industries, Inc.

Fig. 6.14: Luminaires layout plan for CWLED

Exterior Scene 1 / Sport Luminaires (Coordinates List)



Scale 1 : 143

List of the Sport Luminaires

Luminaire	Index	Position [m]			Aiming Point [m]			Angle [°]	Alignment	Pole
		X	Y	Z	X	Y	Z			
Orbit Industries, Inc.	1	10.000	0.000	9.000	0.000	10.000	0.000	32.5	(C 90, G IMax)	/
Orbit Industries, Inc.	1	10.000	0.000	9.000	20.000	10.000	0.000	32.5	(C 90, G IMax)	/

Fig. 6.15: Coordinates list of luminaires for CWLED

- Design Output

The iso-lux diagram for the area under measurement has been shown in **Fig.6.16**.

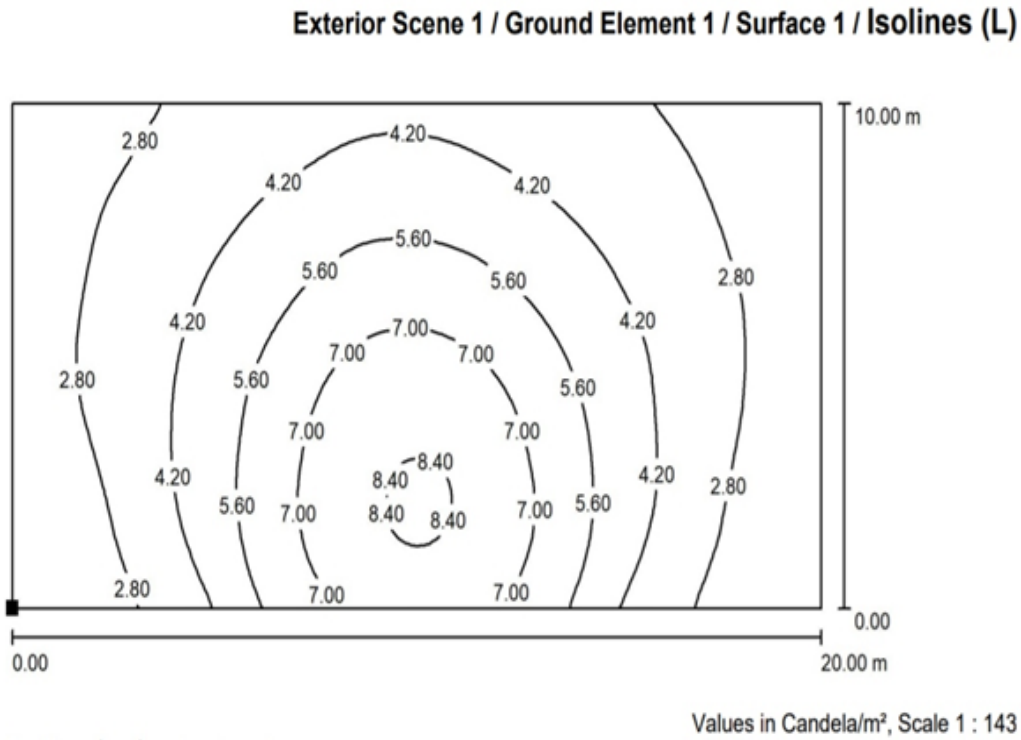


Fig. 6.16: Isolines diagram of the AOM for CWLED

All the point specific photopic luminance value for the AOM has been shown in **Fig.6.17** from the DIALux design output. The corresponding average, maximum and minimum luminance value of the design area are given in the figure. The design parameters obtained throughout the area are as follows:

- Average luminance (L_{avg}) = 4.44 cd/m².
- Overall Uniformity (U_0) = 0.357.

Exterior Scene 1 / Ground Element 1 / Surface 1 / Value Chart (L)

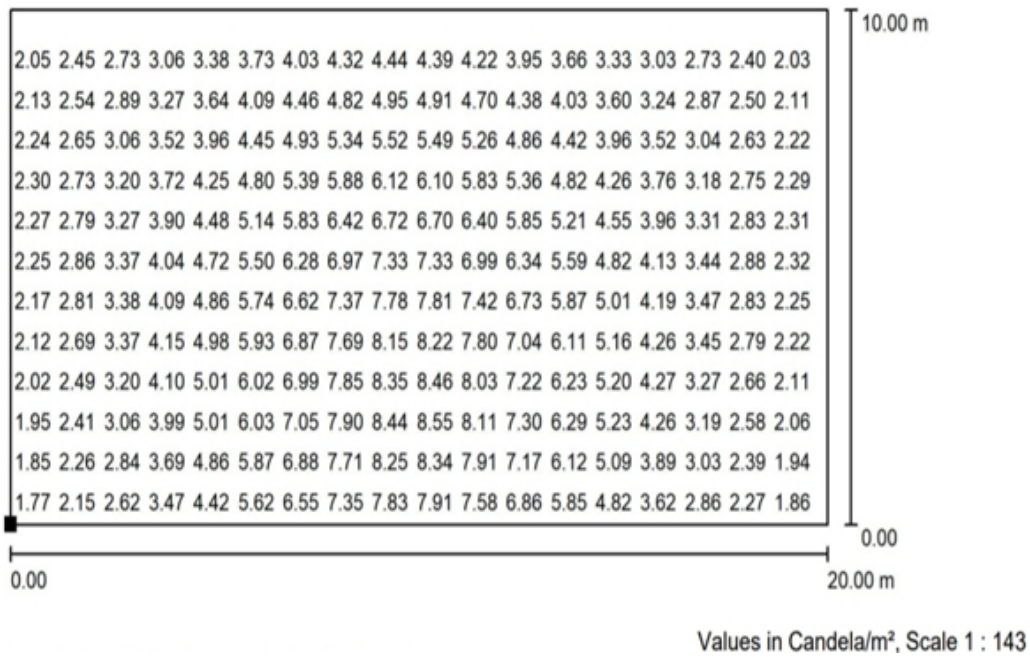


Fig. 6.17: Value chart of point specific photopic luminance for CWLED

6.3.4 Design Summary

All the design parameters from the above three types of design are shown below in **Table 6.8**.

Table 6.6: Design Summary for All the luminaires

MLS	Average photopic luminance (in cd/m ²)	Overall Uniformity
HPSV	1.69	0.265
MH	3.86	0.347
CWLED	4.44	0.357

6.4 Lighting design in mesopic region

As the lighting design can not be done in the software platform for the mesopic region directly, hence it is necessary to use a specifically designed method which can consider the unique characteristics of the

mesopic region, such as the combined effect of both rod and cone vision, to accurately simulate and optimize lighting conditions. The photopic quantities provided by the manufacturer need to be modified for mesopic design through their photometric files. Here the Eulumdat File Format (ldt extension files) [40] has been selected to operate and edit the photometric files with a specific software tool for this file format i.e. the LDT Editor of the DIAL company. All the modified luminaire files have been used in the DIALux lighting simulation software (Version 4.13) (also created by the DIAL company). The steps of the method are given below:

Step 1: After calculating the photopic luminance (L_p) (as shown in section 6.3), corresponding Mesopic luminance (L_m) is calculated using CIE 191:2010 table as shown previously and S/P ratio of the light source.

Step 2: Once the mesopic luminous (L_m) was determined, the Mesopic/Photopic ratio (M/P) was calculated using **Eq. 6.1**.

$$\frac{M}{P} = \frac{K_m \int \phi_{e\lambda} V_{mes}(\lambda) d\lambda}{683 \int \phi_{e\lambda} V(\lambda) d\lambda} \quad (6.1)$$

Step 3: After the determination of the M/P ratio for all the sources, the mesopic values are obtained by multiplying the source luminance values with the M/P ratio. Then the photometric files of the luminaires are edited using the LDT Editor.

Step 4: These edited photometric files are imported in DIALux software and the average luminance is calculated. The flow diagram of the proposed method is shown in **Fig.6.18**.

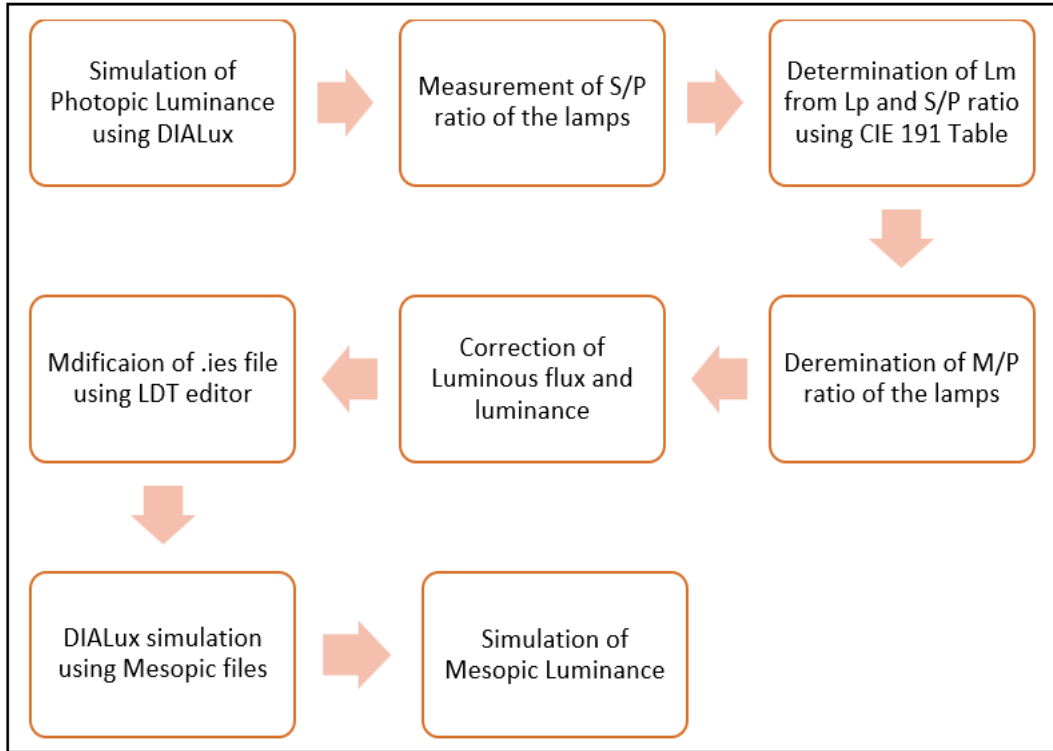


Fig. 6.18: Flow diagram of the mesopic design process

All the measured s/p ratio, calculated mesopic luminance value using CIE 191:2010 and m/p ratio are shown in **Table 6.7**.

Table 6.7: Calculated M/P ratio

Main Light Source	HPSV	MH	CWLED
Average Photopic Luminance (in cd/m ²)	1.69	3.86	4.44
Calculated Mesopic Luminance (in cd/m ²) Using CIE191:2010	1.634	3.88	4.61
Measured S/P Ratio	0.48	1.32	2.02
Calculated M/P Ratio	0.97	1.01	1.04

6.4.1 Design using high-pressure sodium vapour lamp (HPSV)

The layout, type of lamps, luminaires in this case are same as the design in photopic region. The iso-lux diagram for the area under measurement has been shown in **Fig.6.19**. All the point specific mesopic luminance value for the AoM has been shown in **Fig.6.20** from the DIALux design output. The design parameters obtained throughout

the area are as follows:

-Average luminance (L_{avg}) = 1.64 cd/m².

-Overall Uniformity (U_0) = 0.264.

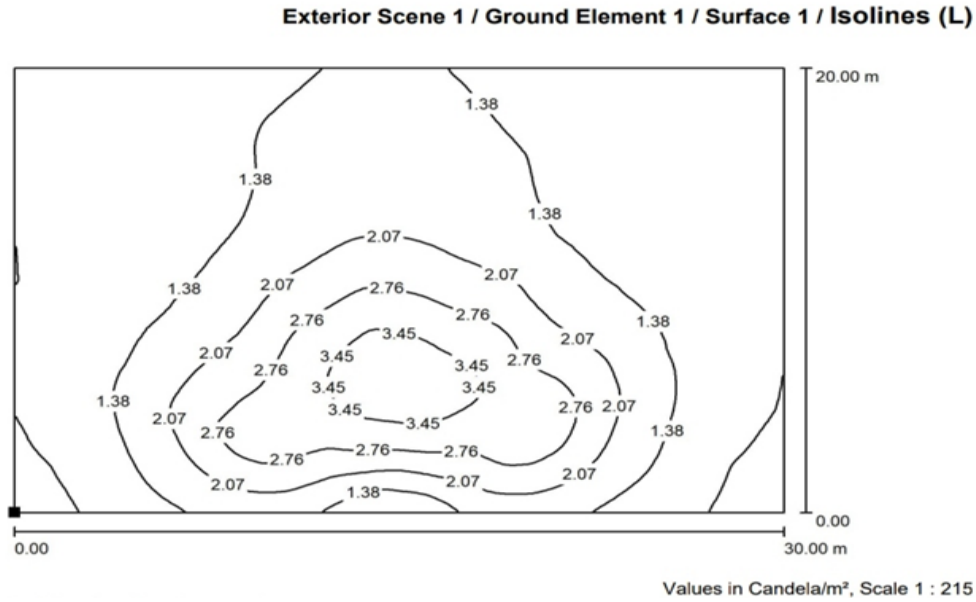


Fig. 6.19: Isolux diagram of the AoM

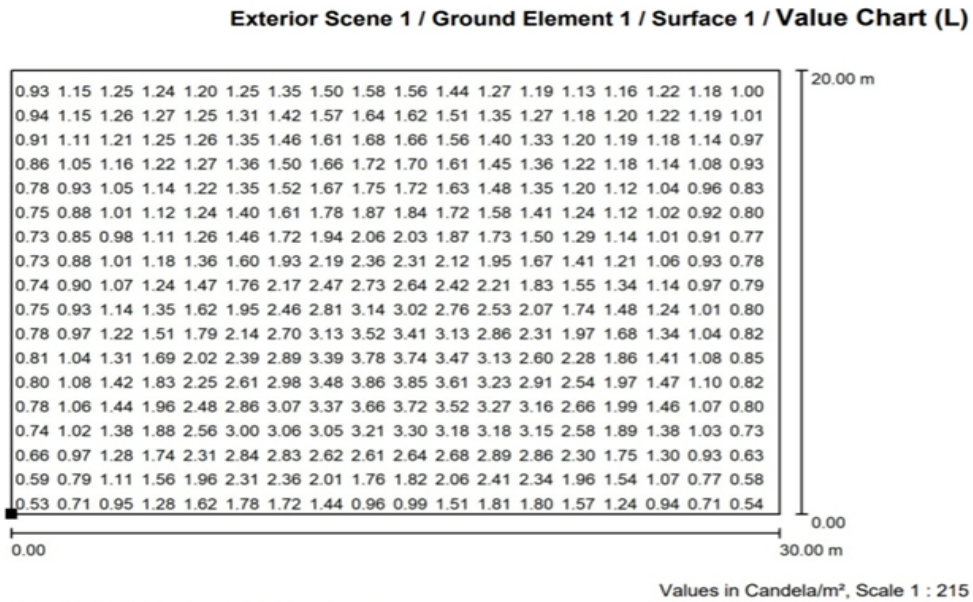


Fig. 6.20: Value chart for HPSV

6.4.2 Lighting Design Using Metal Halide lamp (MH)

The layout, type of lamps, luminaires in this case are same as the design in photopic region. The iso-lux diagram for the area under measurement has been shown in **Fig.6.21**. All the point specific mesopic luminance value for the AoM has been shown in **Fig.6.22** from the DIALux design output. The design parameters obtained throughout the area are as follows:

- Average luminance (L_{avg}) = 3.88 cd/m².
- Overall Uniformity (U_0) = 0.346.

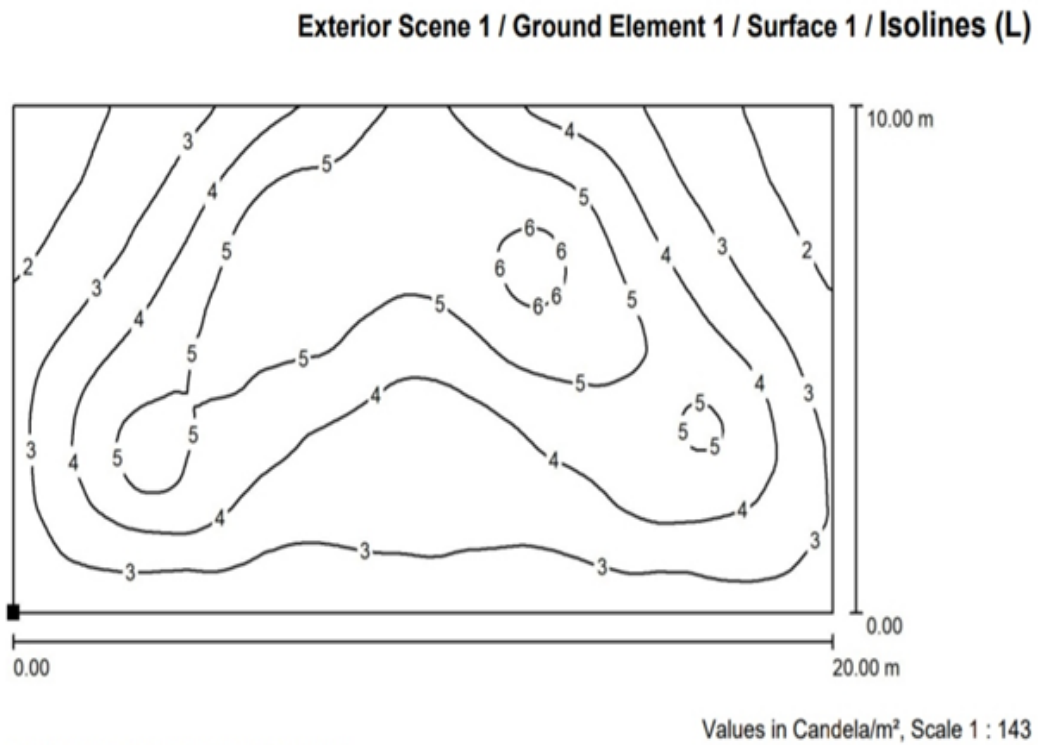


Fig. 6.21: Isolux diagram of the AoM for MH

Exterior Scene 1 / Ground Element 1 / Surface 1 / Value Chart (L)

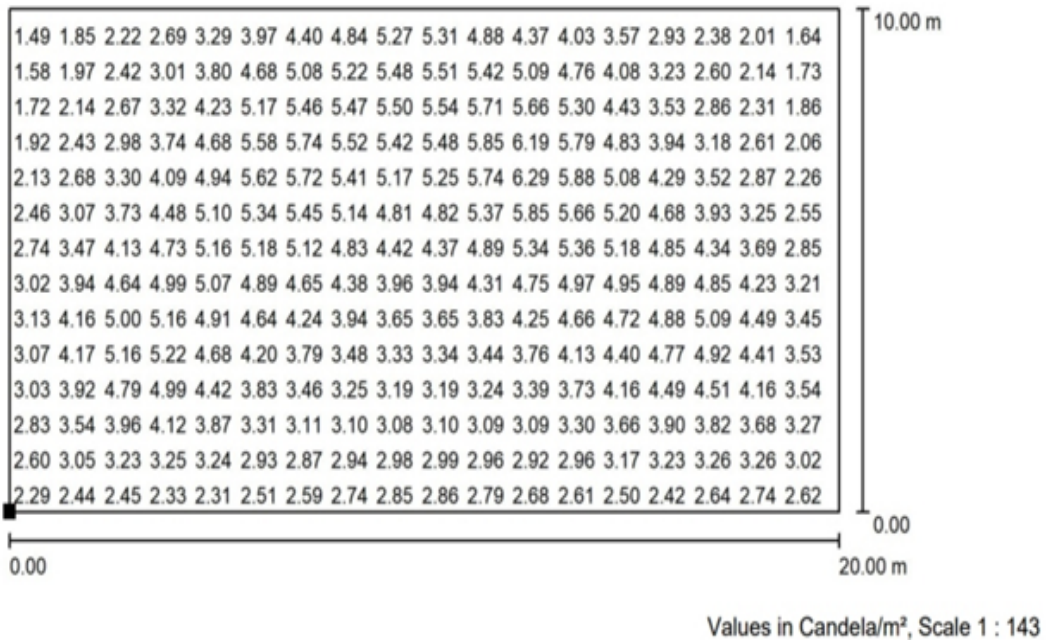


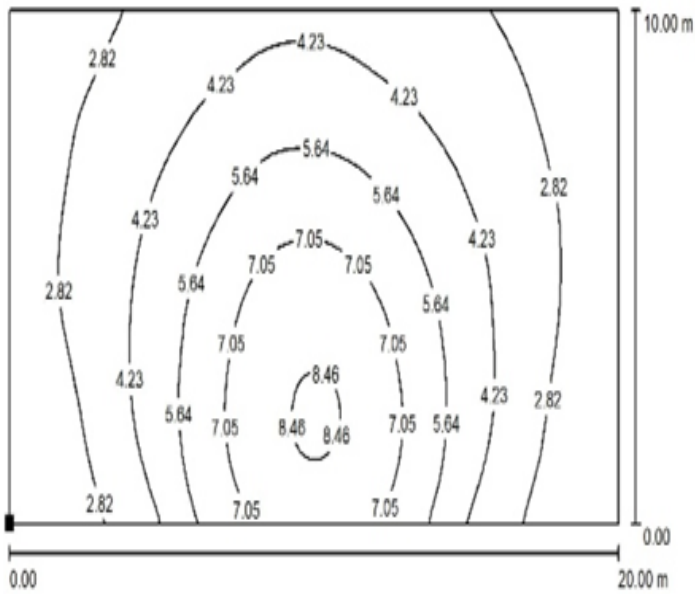
Fig. 6.22: Value chart for MH

6.4.3 Lighting Design using Cool White LED(CWLED)

The layout, type of lamps, luminaires in this case are same as the design in photopic region. The iso-lux diagram for the area under measurement has been shown in **Fig.6.23**. All the point specific mesopic luminance value for the AoM has been shown in **Fig.6.24** from the DIALux design output. The design parameters obtained throughout the area are as follows:

- Average luminance (L_{avg}) = 4.46 cd/m².
- Overall Uniformity (U_0) = 0.357.

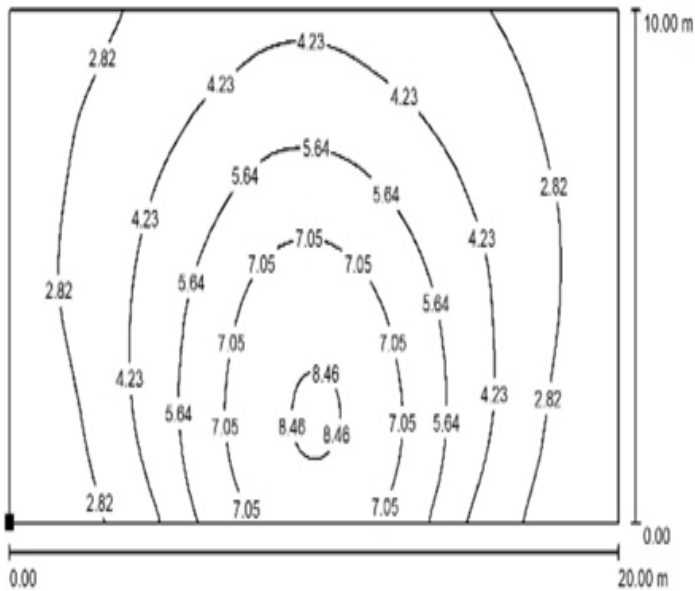
Exterior Scene 1 / Ground Element 1 / Surface 1 / Isolines (L)



Values in Candela/m². Scale 1 : 143

Fig. 6.23: Isolux diagram of the AoM for CWLED

Exterior Scene 1 / Ground Element 1 / Surface 1 / Isolines (L)



Values in Candela/m². Scale 1 : 143

Fig. 6.24: Value chart for CWLED

6.4.4 Design Summary for All the luminaires

All the design parameters from the above three types of design are shown below in **Table 6.8**.

Table 6.8: Design Summary for All the luminaires

Main Light source	Average mesopic luminance (in cd/m^2)	Overall Uniformity
HPSV	1.64	0.264
MH	3.88	0.346
CWLED	4.46	0.357

6.5 Comparison of average luminance

Table 6.9: Average luminance values for different lamps

Main source	L_p (cd/m^2)	L_m (cd/m^2)	L_{ms} (cd/m^2)
HPSV	1.69	1.63	1.64
MH	3.86	3.88	3.88
CWLED	4.44	4.47	4.46

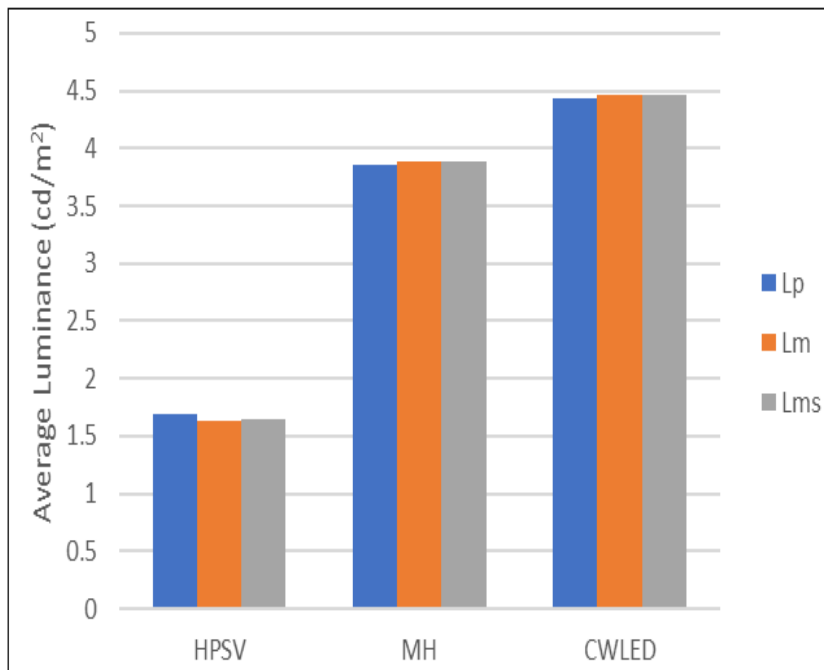


Fig. 6.25: Comparison of L_p , L_m , L_{ms} for different lamps

The average photopic luminance (L_p) achieved from the DIALux design, calculated mesopic luminance (L_m) from the corresponding L_p using CIE191:2010 table & simulated mesopic luminance (L_{ms}) from DIALux design are compared for 3 different set of MLS i.e. HPSV, MH and CWLED lamps. Average photopic luminance (L_p), calculated mesopic luminance (L_m) & simulated mesopic luminance (L_{ms}) values are shown in **Table 6.9** and **Fig. 6.25**.

- **Computation of Adaptation luminance**

Table 6.10: Design Summary

Main source	HPSV	MH	CWLED
Simulated photopic luminance (L_p)	1.69	3.86	4.44
Calculated veiling luminance (L_{veil})	0.17	0.09	0.19
Calculated Adaptation luminance (L_{a1})	1.86	3.93	4.63
Calculated Adaptation luminance from MATLAB (L_a)	1.89	3.41	4.69

Keeping all the other factors the same as discussed in Chapter 3, the veiling luminance created due to the surrounding sources are computed using DIALAX 4.13 software. The field is considered the same as before and the veiling luminance has been computed for the observer. This analysis helps in understanding the impact of veiling luminance on the observer's visibility and allows for adjustments to be made to improve the overall visual experience. Additionally, the data obtained from this analysis as shown in **Table 6.10** can be used to optimize lighting design and compute the adaptation luminance in mesopic region.

6.5.1 Validation of the proposed Model

In **Fig. 6.26**, the 1st bar denotes the average adaptation luminance (L_{a1}) obtained from corresponding photopic luminance and veiling luminance. The 2nd bar shows the average adaptation luminance as computed using MATLAB software using the proposed model for all

three type of lamps. Here it can be observed that both the values closely aligns and the difference is negligible. This suggests that the proposed model can predict the adaptation luminance values for different type of lamps in accordance with the standards set by CIE 191:2010. Therefore, it can be concluded that the proposed method is reliable and meets the necessary criteria for mesopic lighting design.

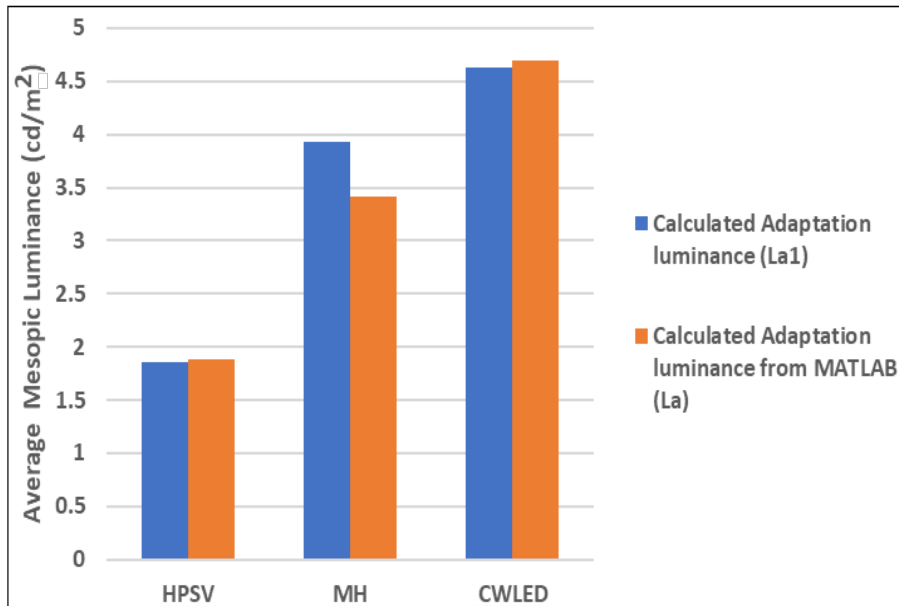


Fig. 6.26: Comparison of La and La1 for different lamps

6.6 Energy Evaluation

The simulated results of The sample area using DIALux 4.13 software for four different designs with different lamps meeting the required standard values as per relevant CIE and IS standards are analysed. The observer position is taken as per CIE standard i.e. at 60m distance in each lane and on the middle of the lane to compute the road surface luminance. The simulated photopic luminance values are converted to mesopic luminance as a function of the relevant photopic luminance and lamp S/P ratio. The comparison of the unit power density (UPD) values is shown in **Fig. 6.27**. Here it is clear that the energy efficiency considering the mesopic effect is maximum in the case of white

LED. For the adaptation luminance due to the higher S/P ratio the blue content is more in CWLED, hence it provides minimum UPD value and better performance under mesopic conditions and can be used to provide more road surface luminance under mesopic condition with same visibility. The combination of CWLED and CWFTL shows minimum UPD considering the adaptation luminance for mesopic performance. In this case spectral characteristics of both main and SLS matches so this combination is perfect for mesopic condition. It can be concluded that this combination is best for energy-efficient lighting design in mesopic region.

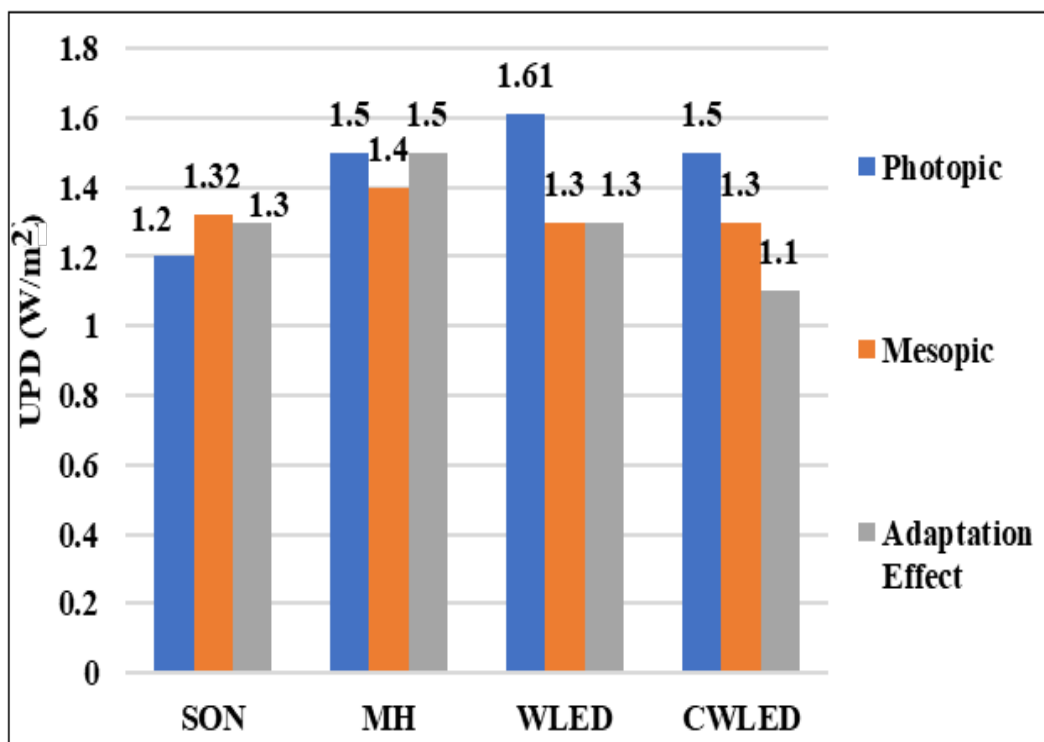


Fig. 6.27: Comparison of UPD values

6.7 Chapter Summary

The main goal of the proposed system is to check the validity of the proposed work in more real scenario. The model has been checked for extensive examples and validation has been checked in software-based design. The output of this chapter can be summarized as:

- The use of mesopic values is introduced in DIALux, a lighting design software traditionally optimized for photopic conditions, and adaptation to mesopic values has been allowed for a more comprehensive analysis in lighting applications.
- The simulated mesopic luminance values generated from DIALux have been compared with the values obtained through interpolation from known photopic luminance values and S/P (Scotopic/Photopic) ratios using the CIE 191-2010 method. It has been found that both the values closely match for a wide range of lighting scenarios.
- Lamps with lower S/P ratios, like High-Pressure Sodium Vapor (HPSV) lamps, exhibit lower L_m (mesopic luminance) values compared to their L_p (photopic luminance) values within the mesopic zone as desired. Consequently, in such environments, the human eye perceives reduced brightness. To attain the same level of brightness, it becomes necessary to use lamps with higher wattage, leading to increased energy consumption. As a result, employing these low S/P ratio lamps in mesopic zones is not advisable from an energy management perspective.
- On the other hand, with certain predefined conditions, the adaptation luminance can be found from the DIALux simulation for different type of lamps. This allows for a more accurate representation of how the lighting will appear in real-life scenarios.

Additionally, by using DIALux simulation, designers can easily compare and evaluate the lighting performance of various lamp to select the most efficient lighting design.

- From the comparison of power consumption in the DIALux design it is clear that lamps with more blue content in its spectrum provides lower UPD value and so shows better performance in the mesopic region and improves more while considering the adaptation luminance effect. This indicates that lamps with shorter wavelengths are more efficient in terms of power consumption and provide enhanced visibility in low light conditions. Additionally, the adaptation luminance effect further enhances the performance of these lamps, making them a more suitable choice for mesopic lighting scenarios.

- **Publication**

Some part of the work discussed in Chapter 6 have been published in the following publication:

Conference Publications: 1

1. Sangita Sahana, Jeenia Dey & Biswanath Roy. 2022. Energy Saving Potential of Lamps with Different Spectral Composition in Outdoor Lighting Applications under Mesopic Photometry System. **IEEE Calcutta Conference (CALCON)**, Kolkata, India, 2022, pp. 175-179, doi: 10.1109/CALCON56258.2022.10059863.

7 Conclusions and Future Scope

7.1 Conclusions

The comprehensive studies conducted on adaptation luminance and lamp performance in the mesopic photometry system have yielded significant insights and findings. These experiments have demonstrated that adaptation luminance plays a crucial role in mesopic vision. It is found that the visual system's sensitivity and performance are highly dependent on the adaptation level, suggesting the need for adaptive lighting systems that adjust to changing luminance conditions. The measurement of mesopic luminance and its application in practical outdoor lighting applications remain beyond the scope of the current photometry system due to established methods and instruments. The photopic luminance is calculated or measured at first. According to various techniques outlined by the CIE and other international standards, corresponding mesopic and adaptation luminance can be further computed.

In the present work, efforts have been made to find the adaptation luminance and analyze the effect of surrounding lighting on the main application area. After carefully reviewing all of the literature that is currently available in the field of study, the problem statement for the current work was developed. The goal is accomplished by carefully following the recommended procedural steps.

With various light sources employed in outdoor lighting applications, the conditions of outdoor lighting have been simulated in **Chapter 3** with the main light source (MLS) and three surrounding light sources (SLSs) to simulate the effect of surrounding lighting on the application area. As found by the increment in adaptation state for set 1

and set 2 of -0.37% and 2.16%, respectively, and so cool white LEDs perform better in the mesopic region. The luminance adaptation to the observer's eyes is largely dependent on the light sources surrounding them. Significant increases in effective brightness occur when the primary light source and surrounding light sources have the same S/P ratio.

In **Chapter 4** the same setup has been developed to find the adaptation luminance of the field. The photopic luminance of the area under measurement was measured and the mesopic and adaptation luminance are computed for different combinations of MLS and SLSs. The scotopic/photopic (S/P) ratio of the installed lamps was used in this work to compute the relevant mesopic luminance values, which were derived from CIE 191:2010 Table. It has been found that in Set 1, where the S/P ratio of MLS and SLS are similar, the increment in adaptation state is 3.65% but when the spectral characteristics are different for both the lamps, i.e. for Set 2, the increment in adaptation state is 2.47%. The effect of the surrounding sources and the primary light source on the observer's adaption state is increased when both lamps have a comparable spectral power distribution. These results demonstrate that optimizing visual performance can be accomplished by carefully analyzing and aligning the S/P ratios of the main and surrounding light sources to produce a significant improvement in effective brightness.

From the detailed analysis in **Chapter 5**, it can be stated that adaptation luminance can be considered instead of mesopic luminance for the fixed area of measurement (AOM). mesopic luminance and adaptation luminance are not the same for the entire area in the presence of surrounding light sources. In comparison to surrounding areas, mesopic luminance is more effective close to the main light source than adaptation luminance. Thus, adaption luminance should be prioritized over

mesopic luminance in any field where veiling sources are present in the line of sight. The position of the surrounding light source within the field of view affects the adaptation luminance as well. As surrounding sources get farther away from the main source and from the observer's viewpoint, the effect of veiling luminance on adaptation luminance varies. Compared to surrounding sources farther away from the main light source, those closer to it induce a greater divergence in adaptation luminance from mesopic luminance.

The adaptation luminance for a real-world scenario involving two MLS and three SLSs combined has been calculated in **Chapter 6**. DIALux 4.13 software has been used to design the area after transforming the photopic luminous flux provided by the luminaire manufacturer into its equivalent mesopic luminous flux and simulating average mesopic luminance values for more comprehensive analysis in lighting applications. Using the CIE 191-2010 technique, the simulated mesopic luminance values produced by DIALux were compared to values derived through interpolation from known photopic luminance values and S/P ratios. For different illumination conditions, it has been found that both values closely match. Lamps with a lower S/P ratio, such as High-Pressure Sodium Vapour (HPSV) provide lower mesopic luminance values in the mesopic zone as desired, in comparison to their photopic luminance values. So Higher wattage lamps must be used to achieve the same luminance, which increases energy consumption. Therefore, from the standpoint of energy management, it is not recommended to use lamps with low S/P ratio in mesopic zones.

Also, the DIALux simulation can yield the adaptation luminance under specific predetermined parameters. So the designers may also quickly compare and assess the lighting performance of different lamps to choose the most effective lighting design by utilizing DIALux simulation. It is evident from the comparison of power consumption in

the DIALux design that lamps with higher blue content in their spectrum have a lower UPD value, which means they perform better in the mesopic area and further improve when the adaptation luminance impact is considered. This suggests that lamps with shorter wavelengths are more energy efficient and improve visibility at low light levels. These lamps work even better in terms of adaptation luminance, which considerably improves their suitability for mesopic lighting conditions. The current experimental approach can be used to assess the performance of various lamps and determine the most effective lighting solutions in mesopic system.

7.2 Future Scope

Future work should focus on collecting and standardizing mesopic lighting data for a wider range of light sources and conditions. This will facilitate more accurate and reliable mesopic design and calculations. User-friendly interface within software platforms can be developed that allows designers to easily switch between photopic and mesopic modes and visualize the impact of mesopic design on their projects. Collaboration with lighting fixture manufacturers to create products specifically designed for mesopic applications, optimizing energy efficiency and performance can be done. Exploration of the integration of light sensors can adapt the lighting system in real-time based on mesopic conditions, enhancing energy efficiency and safety. While this work has provided valuable insights into adaptation luminance and lamp performance in mesopic photometry systems, several avenues for future research and development can be explored. The future scope of research in this field holds significant promise for advancing our understanding of lighting technologies and their impact on human visual performance in various environmental conditions. Beyond the effects of dust, rain, and ambient temperature variations,

which undoubtedly influence lamp performance and visual perception, particular attention should be directed towards assessing the performance of LEDs under foggy weather conditions, as fog presents a unique challenge for visibility. Furthermore, to enhance the accuracy of experimental data, future studies should prioritize the elimination of obstructions and mitigating the effects of reflected light, whether by refining laboratory setups or by conducting experiments in more controlled and real-world outdoor environments. These advancements will contribute to more comprehensive and applicable insights into optimizing lighting solutions for diverse scenarios and environmental challenges. Investigating the potential impacts of mesopic lighting on human health, including its effects on circadian rhythms and sleep patterns, is a burgeoning area of interest. Such research can provide valuable insights into the long-term consequences of mesopic lighting solutions.

The integration of adaptive and intelligent lighting systems stands as a promising future frontier in the study of adaptation luminance and lamp performance in mesopic photometry systems. The development of systems that can dynamically adjust lighting levels and spectral characteristics in response to mesopic conditions, sensor data and advanced algorithms, represents a fertile area for exploration. Such research could not only enhance visual comfort and performance but also leads to significant energy savings and sustainability benefits, ultimately reshaping the landscape of lighting technology and design in the mesopic realm.

Prospective applications of the present study

1. The method can be useful to evaluate the visual adaptation field and to compute adaptation luminance in various outdoor lighting application areas under mesopic vision.
2. The effect of veiling sources and their effect on the adaptation field and the adaptation state of the observer can be evaluated using this approach.
3. The visually effective lighting designs for outdoor lighting applications which are supposed to be more energy efficient compared to photopic aspects can be identified.
4. The outcome of the present work is useful for the implementation of mesopic photometry and analysis of the performance of light sources with different S/P ratios considering mesopic dimensioning.

Annexures

In this section, some of the data obtained from experimentation and simulation during the course of the work, but not presented in the corresponding chapters, are presented. The details of the instruments and lamps used for measurement and computation are also discussed in this section.

Annexure I

1. Adaptation luminance values are simulated for HPSV lamp along with the effect of CWSLEs using MATLAB software. The coding in M-file is shown below:

```
x=[1.5:-0.5:-1];
y=[-2.5:0.5:2.5];
[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
filename = 'Ev for SLE1.xlsx';
Ev = xlsread(filename, 'B3:G13')
L= i.*Ev
filename = 'PHOTOPIC LUMINANCE SON-T.xlsx';
Lp=xlsread(filename, 'B3:G13')
L1=Lp+L
```

Here 'Ev for SLE1' and 'PHOTOPIC LUMINANCE SON-T' are the name of the excel file for vertical illuminance and photopic luminance respectively. $x=[1.5:-0.5:-1];$

```
y=[-2.5:0.5:2.5];
[xx,yy]=meshgrid(x,y);
a=(1.4^2+(yy+6).^2).^0.5
b=(((xx+1.7).^2)+((1-yy).^2)+(2.15^2)).^0.5
c=((0.75^2)+7^2+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
filename = 'Ev for SLE2.xlsx';
Ev = xlsread(filename, 'B3:G13')
L= i.*Ev
filename = 'PHOTOPIC LUMINANCE SON-T.xlsx';
Lp=xlsread(filename, 'B3:G13')
L2=Lp+L

```

Here 'Ev for SLE2' and 'PHOTOPIC LUMINANCE SON-T' are the name of the excel file for vertical illuminance and photopic luminance respectively.

```

x=[1.5:-0.5:-1];
y=[-2.5:0.5:2.5];
[xx,yy]=meshgrid(x,y);
a=(1.4^2+(yy+6).^2).^0.5
b=(((xx+1.7).^2)+((yy+2.5).^2)+(2.15^2)).^0.5
c=(15.7025)^0.5
d=((a.^2)-(b.^2)+(c^2))./(2*c)
e=d./a
theta=acosd(e)
h=theta.^(-3)
i=260*h
filename = 'Ev for SLE3.xlsx';
Ev = xlsread(filename, 'B3:G13')
L3= i.*Ev
filename = 'PHOTOPIC LUMINANCE SON-T.xlsx';
Lp=xlsread(filename, 'B3:G13')

```

$$L_a = L_p + L$$

Here 'E_v for SLE3' and 'PHOTOPIC LUMINANCE SON-T' are the name of the excel file for vertical illuminance and photopic luminance respectively.

$$L = L_1 + L_2 + L_3$$

Similarly mesopic luminance and adaptation luminance are computed from both the luminous intensity distribution data and measured photopic luminance for all the combinations of MLS and SLSs using MATLAB software.

Annexure II

Instruments Used

1. Scotopic/Photopic Meter:

Scotopic/Photopic Ratio for a particular source was measured using Scotopic/Photopic Meter of “SOLAR Light”, Sl. No. 3101 [80] as shown in **Fig1**. This meter has two sensors equipped with CIE $V(\lambda)$ and $V'(\lambda)$ sensitivity functions respectively. It evaluates and shows scotopic and photopic illuminance as seen by the sensor. The S/P ratio of a source can be obtained by dividing the measured scotopic illuminance with photopic illuminance.

Range:: Photopic Detector(PMA 2130):0 to 150000lux
Scotopic Detector(PMA 2131): 0 to 150000lux



Fig1: Scotopic/Photopic Meter

2. Chromometer

For measurements of CCT of the lamps, a Chromameter of “Konica Minolta” Make, Model: CL-200A was used as shown in **Fig2** [83].

Range:: 0.1 to 99990lux, 2000K to 10000K

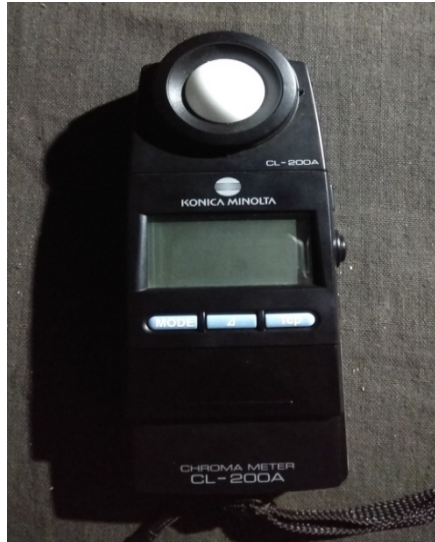


Fig.2: Chromameter

3. Spectroradiometer

Fig3 shows “JETI” make Specbos 1200 Spectroradiometer, which is used to measure the SPD of the light sources.

Specifications: Spectral range-380-780nm.

Calculated wavelength step- 1nm.

Digital electronic resolution- 16Bit ADC(15Bit used).

Viewing angle- 1.8° .

Measuring distance/diameter- 20cm-6mm;100cm-31mm.

Measuring values- Spectral radiance, Total luminance/total radiance, Total illuminance / total irradiance, Chromaticity coordinates x, y, u', v' , CCT, Colour purity, CRI.

Measuring range luminance- $2 \dots 7 \times 10^4 \text{cd/m}^2$.

Measuring range illuminance- $20 \dots 5 \times 10^5 \text{lux}$.

Luminance accuracy- $\pm 2\%$ (@ 100cd/m^2 and illuminant A)

Luminance reproducibility- $\pm 1\%$.

Chromaticity accuracy- ± 0.001 x, y (@ illuminant A).

Color reproducibility- ± 0.0005 x, y .

CCT reproducibility- $\pm 20\text{K}$ (@illuminant A).

Wavelength accuracy- $\pm 0.5\text{nm}$.

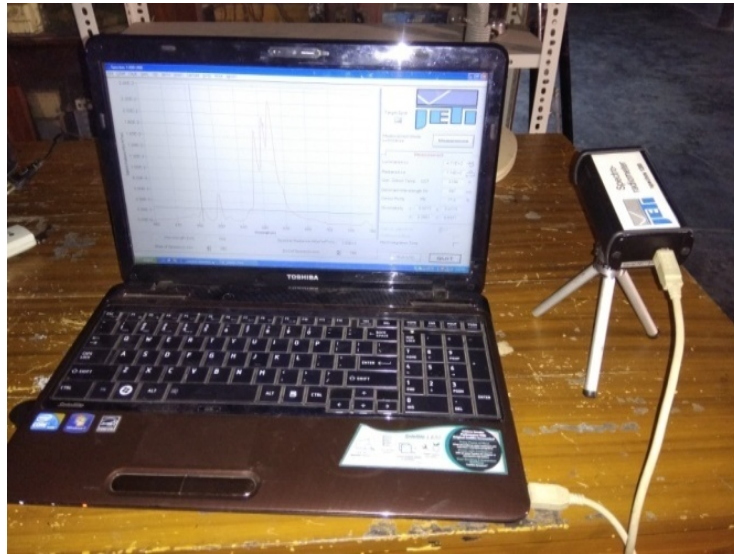


Fig3 Spectroradiometer

4. Luxmeter

Fig4 shows Luxmeter of “Metravi” make, Sl no-1332 & range of 0-200-2k-20k-200k lux is used to measure vertical illuminance of the grid points for the surrounding light sources [84, 85].



Fig 4 Luxmeter

5. Luminance Meter

Fig.5 shows the Luminance Meter of “Konica Minolta” & Model –LS100 [79] used for measurement of luminance.

- Range:: Fast: 0.001 to 299900cd/m² , Slow : 0.001 to 49990 cd/m².



Fig 5 Luminance Meter

6. Programmable AC/DC power source



Fig 6 Programmable AC/DC Power Supply

Variation in input voltage affects the luminous flux output of a lamp. To maintain a constant supply voltage throughout the experimental procedure, a programmable AC/DC power supply of GwINSTEK, Model:APS 1102 was used as shown in **Fig. 6** [86].

Range:: AC I/P :750VA(100 to 180V), 1000VA(180 to 250V)
 DC I/P: 750VA(100 to 180V), 1000VA(180 to 250V)
 AC O/P Voltage: 0 to 155V_{rms}(100V), 0 to 310 V_{rms} (200V)
 DC O/P Voltage: -220V to +220V(100V), -440V to +440V(200V)
 AC O/P Current: 10A(100V),5A(200V)
 DC O/P Current: 10A(100V),5A(200V)
 Frequency: 1Hz to 550Hz.

7. Goniophotometer

For measurements of Luminous Intensity distribution (I-Table) of the lamp , High Precision Rotation Luminaire Goniophotometer (LSG – 1700B) was used in the experiment as shown in **Fig. 7** [78].

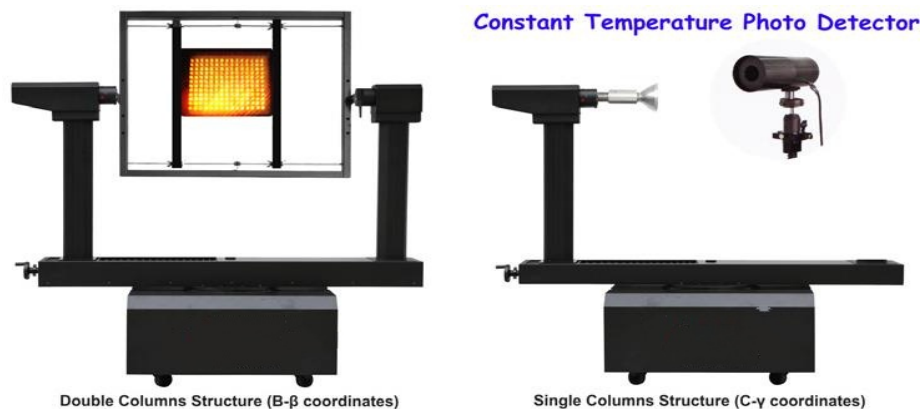


Fig 7 Goniophotometer

SPECIFICATION:

Meets the requirements of CIE, IEC, IES LM-79 & GB standards
 Reaching many measurement ways such as B- and C-
 Luminosity Testing Range: Illuminance 0.001lx~99,999lx; Light Intensity 1.0cd 107cd(detector)
 The accuracy of angle: 0.01°
 Accuracy of photometry: CIE Class A
 Testing Accuracy: 2%(Under Standard lamp); Stray Light: less than 0.1%.

Annexure III

Details of Lamps used

1. HPSV(SON-T)

Details of the HPSV lamp that is used in this experiment are shown below:

Make: Philips

Operating Voltage: 230V ac

Power: Rated- 70W.

Frequency-50Hz

Current- 0.98A

Luminous Flux: Rated- 6000lm

CCT-2000K

Luminous Efficacy- Rated-84lm/W

CRI-35

S/P Ratio-0.48

2. Metal Halide (MH)

Details of the MH lamp that is used in this experiment are shown below.

Make:Philips

Operating Voltage: 230V ac

Power: Rated- 70W.

Frequency-50Hz

Current- 0.98A

Luminous Flux: Rated- 5600lm

CCT-4000K

Luminous Efficacy- Rated-80lm/W

CRI-60

S/P Ratio-1.32

3. White LED (WLED)

Details of the WLED lamp that is used in this experiment are shown below.

Make: Unilux LED Lighting Technologies

Operating Voltage: 230V AC

Current:0.32A

Power:72W

Frequency:50Hz

Power Factor:0.98

CCT:4385K

CRI=87.9

S/P Ratio:1.82

4. Cool White LED(CWLED)

Details of the CWLED lamp that is used in this experiment are shown below.

Make: Unilux LED Lighting Technologies

Operating Voltage: 230V AC

Current:0.32A

Power:72W

Frequency:50Hz

Power Factor:0.98

CCT:5580K

CRI:82.7

S/P Ratio:2.02

5. Surrounding Light Sources (SLS)

Two types of Fluorescent Tube lights (FTL) are used as surrounding light sources:

A. Cool white FTL

B. Warm white FTL.

A. Cool White FTL (CWFTL)

Details of the CW FTL lamps that are used in this experiment are shown below.

Make: Philips

Operating Voltage: 220V ac

Power: Rated- 36W.

Frequency-50Hz

Current- 0.44A

Luminous Flux: Rated- 2500lm

CCT-6200K

Luminous Efficacy- Rated-70lm/W

B. WARM WHITE FTL

Details of the WW FTL lamps that are used in this experiment are shown below.

Make:Philips

Operating Voltage: 220V ac

Power: Rated- 36W.

Frequency-50Hz

Current- 0.44A

Luminous Flux: Rated- 3250lm

CCT-2700K

Luminous Efficacy- Rated-90lm/W

CRI-82

Annexure IV

Measured Data of Photopic Luminance

1. Set 1: CWSLS

Point specific photopic luminance (L_p) values are measured for each MLS and CWSLS (termed as set 1) and the results are shown below:

A. For HPSV Lamp

For HPSV lamp photopic luminance is measured in five different conditions as shown in **Table 4.1**

- i. Measurement of L_p when only HPSV is on.
- ii. Measurement of L_p when HPSV & SLS1 are on.
- iii. Measurement of L_p when HPSV & SLS2 are on.
- iv. Measurement of L_p when HPSV & SLS 3 are on.
- v. Measurement of L_p when HPSV & all SLSs are on.

i. Measurement of L_p when only HPSV is on:

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 1**.

Table 1: Photopic Luminance (in cd/m^2) when only HPSV is on

	A	B	C	D	E	F
1	2	2.5	2.4	1.55	0.85	0.61
2	2.2	2.6	2.35	1.59	0.83	0.53
3	2.25	2.75	2.38	1.71	0.9	0.67
4	2.38	3.35	2.66	1.75	1.03	0.64
5	2.33	3.19	2.69	1.8	0.97	0.78
6	2.6	3.28	3.11	1.92	1.143	0.88
7	2.95	3.16	3.27	2.04	1.28	0.8
8	2.1	3.1	3.09	1.98	1.15	0.74
9	2	2.27	2.66	1.73	1.02	0.75
10	1.4	1.72	2.48	1.52	1	0.78
11	1.33	1.66	2.41	1.47	1.04	0.77

ii. **Measurement of L_p when HPSV & SLS1 on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 2**.

Table 2: Photopic Luminance (in cd/m^2) when HPSV and SLS1 on

	A	B	C	D	E	F
1	2.14	2.49	2.38	1.68	0.84	0.6
2	2.36	2.81	2.38	1.58	0.86	0.56
3	2.42	2.86	2.42	1.79	1	0.68
4	2.52	3.41	2.74	2	1.04	0.67
5	2.6	3.42	2.84	1.9	1.05	0.8
6	2.76	3.33	3.25	2.05	1.15	0.88
7	3	3.54	3.62	2.16	1.27	0.83
8	2.65	3.11	3.54	2.03	1.18	0.76
9	2.3	2.34	3.07	1.88	1.06	0.78
10	1.67	1.95	2.91	1.73	1.03	0.82
11	1.61	2	2.9	1.84	1.11	0.8

iii. **Measurement of L_p when HPSV & SLS2 are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 3**.

Table 3: Photopic Luminance (in cd/m^2) when HPSV and SLS2 on

	A	B	C	D	E	F
1	2.18	2.49	2.42	1.85	0.86	0.61
2	2.44	2.87	2.46	1.65	0.85	0.54
3	2.49	2.97	2.5	1.9	0.98	0.67
4	2.53	3.54	2.9	2.15	1.05	0.66
5	2.61	3.63	2.91	2.02	0.98	0.76
6	2.83	3.46	3.38	2.23	1.18	0.9
7	3.11	3.53	3.61	2.28	1.28	0.8
8	2.31	3.2	3.35	2.15	1.14	0.76
9	2.1	2.42	2.92	1.93	0.99	0.76
10	1.63	1.86	2.74	1.62	1.05	0.79
11	1.43	1.83	2.63	1.67	1	0.77

iv. **Measurement of L_p when HPSV & SLS3 are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 4**.

(v) **Measurement of L_p when HPSV & All SLSs are on**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 5**.

Table 4: Photopic Luminance (in cd/m^2) when HPSV and SLS3 on

	A	B	C	D	E	F
1	2.31	2.62	2.55	1.91	1.14	0.6
2	2.41	2.97	2.56	1.79	1.06	0.59
3	2.49	3.1	2.62	1.9	1.18	0.76
4	2.55	3.37	2.86	2.18	1.17	0.71
5	2.49	3.59	2.93	1.9	1.07	0.83
6	2.65	3.36	3.21	1.96	1.18	0.84
7	2.92	3.33	3.52	2.16	1.31	0.8
8	2.24	3.16	3.21	2	1.16	0.77
9	1.9	2.09	2.71	1.72	1.02	0.76
10	1.4	1.75	2.59	1.54	1.03	0.82
11	1.48	1.72	2.54	1.55	1.1	0.79

Table 5: Photopic Luminance (in cd/m^2) when HPSV and all SLSs on

	A	B	C	D	E	F
1	2.25	3.32	3.18	2.5	1.36	0.83
2	2.66	3.97	3.21	2.23	1.32	0.71
3	2.93	3.56	3.04	2.31	1.2	0.85
4	2.76	3.74	3.43	2.57	1.54	0.83
5	2.84	3.81	3.4	2.3	1.31	0.82
6	3.19	3.9	3.58	2.36	1.38	0.89
7	3.55	4.13	3.64	2.55	1.53	0.9
8	3	3.91	3.88	2.44	1.26	0.74
9	2.84	2.82	3	2.15	1.16	0.73
10	1.8	2.23	2.59	1.73	1.09	0.8
11	1.67	2.03	1.98	1.84	1.1	0.8

B. For MH Lamp:

The above procedure is repeated for MH lamp for five different conditions as shown in **Table 4.1**:

- i. Measurement of L_p when only MH is on
- ii. Measurement of L_p when MH & SLS1 are on.
- iii. Measurement of L_p when MH & SLS2 are on.
- iv. Measurement of L_p when MH & SLS 3 are on.
- v. Measurement of L_p when MH& all SLSs are on.

i. Measurement of L_p when only MH is on:

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 6**.

Table 6: Photopic Luminance (in cd/m^2) when only MH is on

	A	B	C	D	E	F
1	1.61	1.82	2.7	2.57	1.19	0.68
2	1.72	2.47	2.65	2.63	1.19	0.65
3	1.98	2.58	2.8	2.96	1.24	0.8
4	2.25	3.14	2.91	2.82	1.58	0.83
5	2.16	2.99	2.72	2.5	1.46	1.05
6	2	2.67	2.63	2.49	1.36	0.79
7	1.7	1.91	2.1	1.96	1.37	0.75
8	1.28	1.55	1.7	1.38	1.05	0.6
9	1.12	1.25	1.52	1.37	0.85	0.61
10	0.89	1.14	1.33	1.1	0.83	0.64
11	0.82	1.06	1.29	1.18	0.93	0.66

ii. **Measurement of L_p when MH & SLS1 are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 7**.

Table 7: Photopic Luminance (in cd/m^2) when MH & SLS1 on

	A	B	C	D	E	F
1	1.63	1.84	2.73	2.6	1.22	0.71
2	1.76	2.51	2.69	2.68	1.22	0.66
3	2.04	2.65	2.88	3.01	1.3	0.86
4	2.31	3.2	3	2.94	1.66	0.8
5	2.2	3.03	2.8	2.57	1.49	1.06
6	2.09	2.76	2.72	2.64	1.39	0.84
7	1.82	2.05	2.21	2.11	1.46	0.75
8	1.42	1.66	1.81	1.52	1.09	0.6
9	1.22	1.28	1.65	1.5	0.9	0.61
10	1.08	1.33	1.56	1.32	0.87	0.67
11	0.99	1.24	1.56	1.3	0.97	0.66

iii. **Measurement of L_p when MH & SLS2 are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 8**.

iv. **Measurement of L_p when MH & SLS3 are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 9**.

v. **Measurement of L_p when MH & All SLSs are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 10**.

Table 8: Photopic Luminance (in cd/m²) when MH & SLS2 are on

	A	B	C	D	E	F
1	1.69	1.93	2.71	2.65	1.2	0.71
2	1.73	2.54	2.77	2.68	1.19	0.64
3	2.11	2.7	2.95	3.07	1.31	0.81
4	2.45	3.25	3.08	2.98	1.64	0.88
5	2.32	3.12	2.89	2.74	1.49	1.05
6	2.17	2.83	2.7	2.6	1.37	0.84
7	1.86	2.12	2.26	2.19	1.48	0.76
8	1.47	1.74	1.87	1.55	1.09	0.61
9	1.22	1.28	1.67	1.52	0.91	0.62
10	1	1.26	1.5	1.32	0.85	0.66
11	0.91	1.13	1.38	1.3	0.94	0.66

Table 9: Photopic Luminance (in cd/m²) when MH & SLS3 are on

	A	B	C	D	E	F
1	1.7	2.02	2.85	2.7	1.7	0.69
2	1.88	2.68	2.97	2.82	1.34	0.66
3	2.11	2.7	2.93	3.19	1.46	0.81
4	2.27	3.19	3	2.93	1.66	0.84
5	2.21	3.02	2.76	2.56	1.51	1.08
6	2.1	2.7	2.67	2.52	1.38	0.85
7	1.74	2.04	2.13	1.98	1.41	0.76
8	1.33	1.6	1.78	1.42	1.09	0.6
9	1.17	1.26	1.55	1.41	0.87	0.62
10	0.93	1.18	1.37	1.13	0.84	0.65
11	0.83	1.07	1.31	1.19	0.93	0.66

Table 10: Photopic Luminance (in cd/m²) when MH & All SLSs on

	A	B	C	D	E	F
1	1.73	2.1	2.9	2.72	1.72	0.74
2	1.9	2.71	3	2.84	1.36	0.69
3	2.15	2.73	3	3.25	1.47	0.9
4	2.49	3.3	3.12	3.09	1.68	0.88
5	2.35	3.15	2.92	2.83	1.58	1.1
6	2.2	2.89	2.78	2.7	1.45	0.9
7	1.9	2.19	2.34	2.25	1.56	0.8
8	1.53	1.79	1.94	1.6	1.11	0.65
9	1.25	1.32	1.78	1.6	0.99	0.65
10	1.12	1.37	1.66	1.43	0.9	0.7
11	1	1.3	1.66	1.4	1	0.69

C. For White LED (WLED) Lamp

The above procedure is repeated for WLED lamp for five different conditions as shown in **Table 4.1**:

- i. Measurement of L_p when only WLED is on
- ii. Measurement of L_p when WLED & SLS1 are on.
- iii. Measurement of L_p when WLED & SLS2 are on.

iv. Measurement of L_p when WLED & SLS 3 are on.

v. Measurement of L_p when WLED & all SLSs are on.

i. Measurement of L_p when only WLED is on:

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 11**.

Table 11: Photopic Luminance (in cd/m^2) when only WLED is on

	A	B	C	D	E	F
1	2	2.3	2.37	1.83	1.2	0.95
2	2.46	2.8	2.63	1.96	1.35	0.96
3	2.7	2.9	2.64	2.13	1.51	1.18
4	2.94	3.1	2.68	2.23	1.83	1.26
5	2.87	3	2.41	1.85	1.64	1.52
6	2.73	3.1	2.45	1.98	1.57	1.26
7	2.68	2.86	2.23	1.88	1.73	1.09
8	2.07	2.24	1.97	1.46	1.45	0.85
9	2	0.97	1.69	1.47	1.32	0.89
10	1.13	1.41	1.43	1.13	1.01	0.86
11	0.9	0.98	1.12	0.93	0.93	0.78

ii. Measurement of L_p when WLED & SLS1 are on:

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 12**.

Table 12: Photopic Luminance (in cd/m^2) when WLED & SLS1 on

	A	B	C	D	E	F
1	2.01	2.3	2.4	1.85	1.22	0.97
2	2.47	2.82	2.65	1.99	1.37	0.96
3	2.71	2.9	2.64	2.17	1.56	1.21
4	2.95	3.18	2.7	2.27	1.88	1.31
5	2.88	3.03	2.44	1.97	1.66	1.56
6	2.78	3.15	2.5	2.07	1.6	1.29
7	2.68	2.91	2.28	1.96	1.76	1.11
8	2.12	2.33	2.03	1.57	1.48	0.9
9	2.1	2.07	1.79	1.63	1.37	0.89
10	1.2	1.59	1.5	1.3	1.03	0.92
11	1.04	1.12	1.26	1.17	0.96	0.81

iii. Measurement of L_p when WLED & SLS2 are on:

Photopic luminance (L_p) for all the grid points is measured (in cd/m^2) and listed below in **Table 13**.

Table 13: Photopic Luminance (in cd/m^2) when WLED & SLS2 on

	A	B	C	D	E	F
1	2.02	2.34	2.4	1.84	1.23	1
2	2.5	2.83	2.65	2	1.37	0.96
3	2.74	3	2.7	2.18	1.54	1.22
4	3	3.16	2.84	2.38	1.81	1.21
5	2.92	3.11	2.48	1.96	1.66	1.55
6	2.74	3.2	2.61	2.17	1.61	1.15
7	2.76	3.11	2.45	2.09	1.7	1.11
8	2.16	2.5	2.14	1.62	1.46	0.92
9	2.24	1.83	1.96	1.6	1.25	0.89
10	1.26	1.52	1.56	1.2	1.04	0.91
11	1	1.1	1.18	1	0.94	0.83

iv. **Measurement of L_p when WLED & SLS3 are on:**

Photopic luminance (L_p) for all the grid points is measured (in cd/m^2) and listed below in **Table 14**.

Table 14: Photopic Luminance (in cd/m^2) when WLED & SLS3 on

	A	B	C	D	E	F
1	2.2	2.58	2.54	2.12	1.52	1.01
2	2.55	3.07	2.77	2.18	1.53	0.96
3	2.83	3.08	2.8	2.33	1.76	1.23
4	2.97	3.32	2.87	2.34	1.94	1.28
5	2.92	3.1	2.5	2	1.73	1.53
6	2.7	3.1	2.53	2.06	1.63	1.27
7	2.75	2.93	2.31	1.94	1.76	1.1
8	2.14	2.34	2.03	1.49	1.43	0.89
9	2.08	2.06	1.73	1.51	1.43	0.96
10	1.15	1.44	1.46	1.17	1.04	0.89
11	0.9	1	1.14	0.95	0.96	0.8

v. **Measurement of L_p when WLED & all SLSs are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 15**.

D. For Cool White LED (CWLED) lamp:

The above procedure is repeated for CWLED lamp for five different conditions as shown in **Table 4.1**:

- i. Measurement of L_p when only WLED is on
- ii. Measurement of L_p when WLED & SLS1 are on.

Table 15: Photopic Luminance(in cd/m^2) when WLED & all SLSs on

	A	B	C	D	E	F
1	2.25	2.64	2.6	2.17	1.57	1.06
2	2.6	3.1	2.81	2.22	1.57	1
3	2.88	3.12	2.85	2.39	1.82	1.28
4	3.04	3.37	2.92	2.4	2	1.34
5	2.97	3.15	2.55	2.04	1.79	1.58
6	2.87	3.25	2.65	2.22	1.69	1.34
7	2.8	3.16	2.5	2.15	1.76	1.17
8	2.25	2.56	2.19	1.68	1.51	0.98
9	2.29	1.94	2.04	1.66	1.31	0.93
10	1.4	1.74	1.7	1.35	1.1	0.99
11	1.1	1.31	1.31	1.23	0.97	0.86

- iii. Measurement of L_p when WLED & SLS2 are on.
- iv. Measurement of L_p when WLED & SLS 3 are on.
- v. Measurement of L_p when WLED & all SLSs are on
- i. Measurement of L_p when only CWLED is on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 16**.

Table 16: Photopic Luminance (in cd/m^2) when only CWLED is on

	A	B	C	D	E	F
1	2.5	2.8	2.82	2.01	1.34	1.02
2	2.82	3.34	2.84	2.1	1.43	1.12
3	3.14	3.53	2.74	2.34	1.6	1.25
4	3.34	3.67	2.88	2.35	1.62	1.29
5	3.19	3.37	2.59	1.95	1.7	1.56
6	3.15	3.31	2.52	2.14	1.61	1.36
7	2.7	3.04	2.36	1.94	1.81	1.11
8	2.38	2.5	2.15	1.55	1.45	0.95
9	1.56	1.77	1.87	1.6	1.21	0.89
10	1.3	1.56	1.48	1.24	1.03	0.85
11	0.97	1.06	1.13	0.96	0.91	0.8

- ii. Measurement of L_p when CWLED & SLS1 are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 17**.

- iii. Measurement of L_p when CWLED & SLS2 are on:**

Table 17: Photopic Luminance (in cd/m^2) when CWLED & SLS1 on

	A	B	C	D	E	F
1	2.52	2.82	2.84	2.03	1.36	1.02
2	2.84	3.36	2.86	2.12	1.46	1.14
3	3.17	3.56	2.78	2.37	1.62	1.27
4	3.39	3.76	2.95	2.35	1.96	1.2
5	3.13	3.5	2.76	2.27	1.74	1.56
6	3.18	3.52	2.64	2.14	1.62	1.36
7	2.97	3.22	2.54	1.97	1.85	1.13
8	2.4	2.52	2.3	1.77	1.5	0.95
9	1.6	1.83	2.06	1.69	1.3	0.9
10	1.4	1.7	1.55	1.29	1.05	0.89
11	1.12	1.25	1.32	1.19	0.95	0.82

Table 18: Photopic Luminance (in cd/m^2) when CWLED & SLS2 on

	A	B	C	D	E	F
1	2.55	2.86	2.89	2.07	1.39	1.07
2	2.87	3.39	3	2.15	1.48	1.2
3	3.2	3.59	3.08	2.41	1.65	1.29
4	3.45	3.89	3.11	2.59	2.09	1.3
5	3.4	3.56	2.84	2.14	1.7	1.58
6	3.34	3.67	2.79	2.39	1.63	1.36
7	2.9/8	3.13	2.61	2.16	1.91	1.13
8	2.42	2.66	2.34	1.78	1.56	0.97
9	1.62	1.94	2.15	1.81	1.29	0.89
10	1.41	1.7	1.67	1.29	1.05	0.88
11	1.02	1.14	1.21	1.05	0.945	0.8

Photopic luminance (L_p) for all the grid points is measured (in cd/m^2) and listed below in **Table 18**.

iv. **Measurement of L_p when CWLED & SLS3 are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 19**.

Table 19: Photopic Luminance (in cd/m^2) when CWLED & SLS3 on

	A	B	C	D	E	F
1	2.65	3.04	3.14	2.29	1.54	1.15
2	3.12	3.64	3.18	2.32	1.58	1.27
3	3.25	3.76	3.01	2.57	1.71	1.36
4	3.5	3.97	3.09	2.6	2.14	1.29
5	3.32	3.58	2.87	2.1	1.84	1.63
6	3.26	3.59	2.7	2.15	1.71	1.36
7	2.99	3.01	2.47	2.05	1.91	1.15
8	2.39	2.51	2.24	1.66	1.55	0.95
9	1.57	1.78	1.9	1.63	1.21	0.89
10	1.31	1.58	1.5	1.26	1.03	0.85
11	0.99	1.08	1.22	1	0.92	0.8

2. Set 2: WWSLS

A. For HPSV Lamp:

For HPSV light source photopic luminances are measured in 2 different conditions as shown in Table 4.1:

- i. Measurement of L_p when only HPSV is on.
- ii. Measurement of L_p when HPSV & all SLSs are on.

i. Measurement of L_p when only HPSV is on:

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 20**.

Table 20: Photopic luminance (in cd/m^2) when only HPSV is on

	A	B	C	D	E	F
1	1.75	2.06	2.07	1.37	0.76	0.41
2	1.49	1.88	1.84	1.07	0.62	0.55
3	1.49	2	1.7	1.2	0.7	0.49
4	1.44	2.1	1.86	1.24	0.73	0.51
5	1.55	2	1.75	1.17	0.76	0.57
6	1.58	1.98	1.73	1.17	0.78	0.63
7	1.57	2.26	2.09	1.26	0.84	0.59
8	1.39	1.99	2.09	1.04	0.74	0.56
9	1	1.42	1.65	0.99	0.7	0.48
10	0.74	1.08	1.34	0.87	0.59	0.48
11	0.68	0.85	1.41	0.76	0.54	0.41

ii. Photopic luminance (in cd/m^2) when HPSV & all SLSs are on:

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 21**.

B. For MH Lamp:

For MH lamp photopic luminance are measured in 2 different conditions as shown in Table 4.1.

- i. Measurement of L_p when only MH is on.
- ii. Measurement of L_p when MH & all SLSs are on.

Table 21: Photopic luminance (in cd/m^2) when HPSV & all SLSs on

	A	B	C	D	E	F
1	2	2.51	2.63	2	1.29	0.46
2	1.87	2.39	2.36	1.54	1.02	0.65
3	1.92	2.47	2.19	1.82	1.05	0.55
4	1.85	2.54	2.4	1.84	1.05	0.58
5	1.98	2.48	2.28	1.78	1.02	0.62
6	2.01	2.42	2.28	1.81	1	0.72
7	1.95	2.81	2.62	1.88	1.07	0.665
8	1.94	2.55	2.79	1.6	0.93	0.58
9	1.5	1.95	2.32	1.54	0.88	0.54
10	1.13	1.56	2.08	1.36	0.72	0.56
11	1.01	1.31	2.04	1.2	0.65	0.47

Table 22: Photopic luminance (in cd/m^2) when only MH is on

	A	B	C	D	E	F
1	0.9	1.7	2.23	2.03	0.88	0.38
2	0.97	1.4	1.93	1.46	0.65	0.5
3	1.04	1.38	1.68	1.58	0.71	0.42
4	1	1.43	1.67	1.61	0.79	0.44
5	0.98	1.43	1.54	1.53	0.78	0.47
6	1.09	1.44	1.51	1.47	0.82	0.51
7	0.93	1.47	1.57	1.53	0.93	0.51
8	0.78	1.14	1.4	1.11	0.73	0.44
9	0.7	0.93	1.13	0.99	0.61	0.43
10	0.49	0.71	0.97	0.77	0.51	0.41
11	0.48	0.64	0.96	0.62	0.49	0.35

i. Measurement of L_p when only MH is on:

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 22**.

ii. Measurement of L_p when MH & all SLSs are on:

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 23**.

Table 23: Photopic luminance (in cd/m^2) when MH & all SLSs are on

	A	B	C	D	E	F
1	1.3	2.01	2.86	2.46	1.28	0.43
2	1.36	1.75	2.32	1.94	1	0.56
3	1.35	1.79	2.1	2.12	1.03	0.49
4	1.29	1.83	2.13	2.15	1.06	0.47
5	1.39	1.8	1.96	2.05	0.99	0.52
6	1.4	1.8	1.94	1.89	1.01	0.59
7	1.37	1.86	2.01	1.99	1.1	0.57
8	1.19	1.57	1.83	1.57	0.93	0.5
9	0.9	1.29	1.68	1.39	0.75	0.46
10	0.8	1.12	1.51	1.13	0.63	0.48
11	0.74	1.01	1.47	0.97	0.59	0.41

C. For White LED (WLED) Lamp:

For WLED lamp photopic luminance are measured in 2 different conditions as shown in Table 4.3:

- i. Measurement of L_p when only WLED is on.
 - ii. Measurement of L_p when WLED & all SLSs are on.
- i. **Measurement of L_p when only WLED is on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 24**.

Table 24: Photopic luminance (in cd/m^2) when only WLED is on

	A	B	C	D	E	F
1	2.6	2.74	2.53	1.95	1.42	0.81
2	2.53	2.7	2.43	1.68	1.29	1.19
3	2.59	2.79	2.38	2.12	1.53	1.14
4	2.48	2.79	2.47	2.1	1.65	1.2
5	2.47	2.51	2.1	1.9	1.63	1.28
6	2.51	2.28	2	1.74	1.53	1.34
7	2.14	2.45	2.13	1.64	1.57	1.22
8	1.85	2.13	2.08	1.28	1.24	0.98
9	1.75	1.67	1.75	1.22	1.04	0.82
10	0.99	1.18	1.34	1.01	0.89	0.8
11	0.88	0.86	1	0.82	0.73	0.6

- ii. **Measurement of L_p when WLED & all SLSs are on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 25**.

Table 25: Photopic luminance (in cd/m^2) when WLED & all SLSs on

	A	B	C	D	E	F
1	3.1	3.26	3.07	2.58	1.93	0.87
2	2.95	3.11	2.98	2.36	1.7	1.36
3	3.07	3.28	2.91	2.74	1.91	1.22
4	2.92	3.3	3.01	2.64	1.93	1.28
5	2.97	3	2.64	2.48	1.91	1.38
6	2.97	2.75	2.53	2.27	1.8	1.45
7	2.6	3.02	2.76	2.25	1.79	1.29
8	2.3	2.75	2.83	1.77	1.48	1.09
9	2	2.15	2.47	1.71	1.22	0.89
10	1.4	1.63	2.01	1.5	0.98	0.87
11	1.22	1.39	1.55	1.21	0.82	0.67

D. For CWLED lamp

i. **Measurement of L_p when only CWLED is on:**

Photopic luminance (L_p) for all the grid points is measured and listed below in **Table 26**.

Table 26: Photopic luminance (in cd/m^2) when only CWLED is on

	A	B	C	D	E	F
1	2.53	2.96	2.7	2.03	1.44	0.77
2	2.6	2.73	2.59	1.72	1.3	1.15
3	2.69	2.74	2.42	2.14	1.56	1.07
4	2.5	2.72	2.47	2.1	1.62	1.14
5	2.38	2.55	2.19	1.91	1.63	1.24
6	2.39	2.27	1.93	1.69	1.49	1.26
7	2.03	2.21	2.02	1.68	1.49	1.15
8	1.81	1.91	1.75	1.24	1.3	0.96
9	1.2	1.54	1.58	1.2	1.06	0.76
10	0.93	1.22	1.26	1	0.87	0.74
11	0.8	0.85	0.96	0.78	0.69	0.57

Annexure V

Computed Data of Mesopic Luminance

1. Set-1:MLS & CWSLS

A. For HPSV Lamp:

Mesopic luminance values are calculated for HPSV lamp along with all the SLSs from the corresponding measured photopic luminance data and listed below in **Table 1**.

Table 1: Mesopic luminance (in cd/m^2) when HPSV and all SLSs on

	A	B	C	D	E	F
1	2.2	3.27	3.13	2.45	1.31	0.78
2	2.61	3.92	3.16	2.18	1.27	0.66
3	2.88	3.51	2.99	2.26	1.15	0.8
4	2.71	3.69	3.38	2.52	1.49	0.78
5	2.79	3.76	3.35	2.25	1.26	0.77
6	3.14	3.85	3.53	2.31	1.33	0.84
7	3.5	4.08	3.59	2.5	1.48	0.85
8	2.95	3.86	3.83	2.39	1.21	0.69
9	2.79	2.77	2.95	2.1	1.11	0.68
10	1.75	2.18	2.54	1.68	1.04	0.75
11	1.62	1.98	1.94	1.79	1.05	0.75

B. For MH Lamp

Mesopic luminance values are calculated for MH lamp along with all the SLSs from the corresponding measured photopic luminance data and listed below in **Table 2**.

Table 2: Mesopic luminance (in cd/m^2) when MH and all SLSs are on

	A	B	C	D	E	F
1	1.76	2.13	2.93	2.75	1.75	0.77
2	1.93	2.74	3.03	2.87	1.39	0.72
3	2.18	2.76	3.03	3.28	1.5	0.93
4	2.52	3.33	3.15	3.12	1.71	0.91
5	2.38	3.18	2.95	2.86	1.61	1.13
6	2.23	2.92	2.81	2.73	1.48	0.93
7	1.93	2.22	2.37	2.28	1.59	0.83
8	1.56	1.82	1.97	1.63	1.14	0.68
9	1.28	1.35	1.81	1.63	1.02	0.68
10	1.15	1.4	1.69	1.46	0.93	0.73
11	1.03	1.33	1.69	1.43	1.03	0.72

C. For WLED Lamp

Mesopic luminance values are calculated for WLED lamp along with all the SLSs from the corresponding measured photopic luminance data and listed below in **Table 3**.

Table 3: Mesopic luminance (in cd/m^2) when WLED and all SLSs on

	A	B	C	D	E	F
1	2.33	2.72	2.68	2.25	1.65	1.14
2	2.68	3.17	2.88	2.3	1.65	1.08
3	2.95	3.19	2.92	2.47	1.9	1.36
4	3.11	3.43	2.99	2.48	2.08	1.42
5	3.04	3.22	2.63	2.12	1.87	1.66
6	2.95	3.31	2.73	2.3	1.77	1.42
7	2.88	3.23	2.56	2.23	1.84	1.25
8	2.33	2.64	2.27	1.76	1.59	1.06
9	2.37	2.02	2.12	1.74	1.39	1.01
10	1.48	1.82	1.78	1.43	1.18	1.07
11	1.18	1.39	1.39	1.31	1.05	0.94

2. Set-2: MLS & WWSLS:

A. For HPSV Lamp:

Table 4: Mesopic luminance (in cd/m^2) when HPSV and all SLSs on

	A	B	C	D	E	F
1	1.95	2.46	2.58	1.95	1.24	0.41
2	1.82	2.34	2.31	1.49	0.97	0.6
3	1.87	2.42	2.14	1.77	1	0.5
4	1.8	2.49	2.35	1.79	1	0.53
5	1.93	2.43	2.23	1.73	0.97	0.57
6	1.96	2.37	2.23	1.76	0.95	0.67
7	1.9	2.76	2.57	1.83	1.02	0.61
8	1.89	2.5	2.74	1.55	0.88	0.53
9	1.45	1.9	2.27	1.49	0.83	0.49
10	1.08	1.51	2.03	1.31	0.67	0.51
11	0.96	1.26	1.99	1.15	0.6	0.42

Mesopic luminance values are calculated for HPSV lamp along with all the SLSs from the corresponding measured photopic luminance data and listed below in **Table 4**.

B. For MH Lamp:

Mesopic luminance values are calculated for MH lamp along with all the SLSs from the corresponding measured photopic luminance data and listed below in **Table 5**.

Table 5: Mesopic luminance (in cd/m^2) when MH and all SLSs are on

	A	B	C	D	E	F
1	1.33	2.04	2.89	2.49	1.31	0.46
2	1.39	1.78	2.35	1.97	1.03	0.59
3	1.38	1.82	2.15	2.15	1.06	0.52
4	1.32	1.86	2.16	2.18	1.09	0.5
5	1.42	1.83	1.99	2.08	1.02	0.55
6	1.43	1.83	1.97	1.92	1.04	0.62
7	1.4	1.89	2.04	2.02	1.13	0.6
8	1.22	1.6	1.86	1.6	0.96	0.53
9	0.93	1.32	1.71	1.42	0.78	0.49
10	0.83	1.15	1.54	1.16	0.66	0.51
11	0.77	1.04	1.5	1	0.62	0.44

Annexure VI

Computed Data of Adaptation Luminance

1. Set-1: MLS & CWSLS

A. For HPSV Lamp:

For HPSV light source adaptation luminance is simulated in four different conditions as shown in Table 4.1:

- i. Measurement of L_a when HPSV & SLS1 are on.
- ii. Measurement of L_a when HPSV & SLS2 are on.
- iii. Measurement of L_a when HPSV & SLS3 are on.
- iv. Measurement of L_a when HPSV & all SLSs are on.

i. Measurement of L_a when HPSV & SLS1 are on:

Adaptation luminance values are simulated for HPSV lamp along with the effect of SLSs and listed below in **Table 1**.

Table 1: Adaptation luminance (in cd/m^2) when HPSV and SLS1 on

	A	B	C	D	E	F
1	2.00	2.50	2.40	1.55	0.85	0.61
2	2.20	2.60	2.35	1.59	0.83	0.53
3	2.26	2.76	2.38	1.71	0.91	0.67
4	2.39	3.36	2.67	1.75	1.03	0.64
5	2.34	3.20	2.70	1.81	0.97	0.79
6	2.62	3.31	3.13	1.97	1.13	0.89
7	2.98	3.21	3.31	2.10	1.32	0.81
8	2.16	3.18	3.18	2.10	1.25	0.75
9	2.09	2.40	2.84	1.97	1.18	0.76
10	1.53	1.92	2.79	1.99	1.45	0.79
11	1.52	1.98	2.96	2.32	1.91	0.81

ii. Measurement of L_a when HPSV & SLS2 are on:

Adaptation luminance (L_a) for all the grid points (in cd/m^2) is listed below in **Table 2**.

iii. Measurement of L_a when HPSV & SLS3 are on:

Adaptation luminance values are simulated for HPSV lamp along with the effect of SLSs and listed below in **Table 3**.

iv. Measurement of L_a when HPSV & all SLSs are on:

Table 2: Adaptation luminance (in cd/m^2) when HPSV and SLS2 on

	A	B	C	D	E	F
1	2.01	2.51	2.41	1.61	0.86	0.61
2	2.21	2.62	2.37	1.71	0.84	0.53
3	2.27	2.78	2.42	1.96	0.94	0.68
4	2.42	3.40	2.74	2.16	1.14	0.67
5	2.38	3.28	2.85	2.27	1.29	0.91
6	2.67	3.41	3.36	2.33	1.81	1.10
7	3.04	3.32	3.59	2.33	2.36	1.25
8	2.19	3.28	3.40	2.13	2.25	1.18
9	2.09	2.43	2.95	1.81	1.75	0.99
10	1.47	1.86	2.71	1.59	1.34	0.82
11	1.40	1.77	2.54	1.51	1.19	0.80

Table 3: Adaptation luminance (in cd/m^2) when HPSV and SLS3 on

	A	B	C	D	E	F
1	2.02	2.54	2.47	1.69	1.07	0.79
2	2.22	2.64	2.42	1.73	1.06	0.71
3	2.27	2.79	2.44	1.82	1.05	0.77
4	2.40	3.38	2.71	1.82	1.09	0.68
5	2.35	3.21	2.73	1.84	1.01	0.79
6	2.61	3.30	3.13	1.95	1.15	0.89
7	2.96	3.17	3.29	2.06	1.29	0.80
8	2.11	3.11	3.10	1.99	1.16	0.74
9	2.01	2.28	2.67	1.74	1.02	0.75
10	1.40	1.72	2.48	1.52	1.00	0.78
11	1.33	1.66	2.41	1.47	1.04	0.77

Table 4: Adaptation luminance (in cd/m^2) when HPSV and all SLSs are on

	A	B	C	D	E	F
1	2.02	2.55	2.48	1.75	1.08	0.79
2	2.23	2.66	2.45	1.85	1.07	0.72
3	2.29	2.82	2.48	2.06	1.09	0.78
4	2.44	3.44	2.79	2.24	1.20	0.71
5	2.41	3.31	2.90	2.32	1.33	0.93
6	2.71	3.46	3.40	2.41	1.83	1.11
7	3.08	3.38	3.65	2.40	2.41	1.26
8	2.26	3.37	3.50	2.26	2.36	1.19
9	2.19	2.58	3.14	2.06	1.91	1.00
10	1.60	2.06	3.02	2.06	1.79	0.83
11	1.59	2.10	3.09	2.36	2.06	0.84

Adaptation luminance values are simulated for HPSV lamp along with the effect of SLSs and listed below in **Table 4**.

B. For MH Lamp:

For MH lamp adaptation luminances are simulated in 4 different conditions:

- i. Measurement of L_a when MH & SLS1 are on.

ii. Measurement of L_a when MH & SLS2 are on.

iii. Measurement of L_a when MH & SLS3 are on.

iv. Measurement of L_a when MH & all SLSs are on.

i. Measurement of L_a when MH & SLS1 are on:

Adaptation luminance values are simulated for MH lamp along with the effect of SLS1 and listed below in **Table 5**.

Table 5: Adaptation luminance (in cd/m^2) when MH and SLS1 on

	A	B	C	D	E	F
1	1.61	1.82	2.7	2.57	1.19	0.68
2	1.72	2.47	2.65	2.64	1.19	0.65
3	1.99	2.59	2.8	2.96	1.25	0.8
4	2.26	3.15	2.92	2.82	1.58	0.83
5	2.17	3	2.73	2.51	1.46	1.06
6	2.02	2.7	2.65	2.54	1.36	0.8
7	1.73	1.96	2.14	2.02	1.41	0.76
8	1.34	1.63	1.79	1.5	1.15	0.61
9	1.21	1.39	1.7	1.61	1.01	0.62
10	1.02	1.34	1.64	1.57	1.28	0.65
11	1.01	1.38	1.84	2.03	1.8	0.7

ii. Measurement of L_a when MH & SLS2 are on:

Adaptation luminance values are simulated for MH lamp along with the effect of SLS2 and listed below in **Table 6**.

Table 6: Adaptation luminance (in cd/m^2) when MH and SLS2 on

	A	B	C	D	E	F
1	1.62	1.83	2.72	2.63	1.2	0.68
2	1.73	2.49	2.67	2.76	1.2	0.65
3	2	2.61	2.84	3.21	1.28	0.81
4	2.29	3.19	3	3.23	1.69	0.86
5	2.21	3.08	2.88	2.97	1.78	1.18
6	2.07	2.8	2.88	2.9	2.04	1.01
7	1.79	2.07	2.42	2.25	2.45	1.2
8	1.37	1.73	2.01	1.53	2.15	1.04
9	1.21	1.41	1.81	1.45	1.58	0.85
10	0.96	1.28	1.56	1.17	1.17	0.68
11	0.89	1.17	1.42	1.22	1.08	0.69

iii. Measurement of L_a when MH & SLS 3 are on:

Table 7: Adaptation luminance (in cd/m^2) when MH and SLS3 on

	A	B	C	D	E	F
1	1.63	1.86	2.77	2.71	1.41	0.86
2	1.74	2.51	2.72	2.78	1.42	0.83
3	2	2.62	2.86	3.07	1.39	0.9
4	2.27	3.17	2.96	2.89	1.64	0.87
5	2.18	3.01	2.76	2.54	1.5	1.06
6	2.01	2.69	2.65	2.52	1.38	0.8
7	1.71	1.92	2.12	1.98	1.38	0.75
8	1.29	1.56	1.71	1.39	1.06	0.6
9	1.13	1.26	1.53	1.38	0.85	0.61
10	0.89	1.14	1.33	1.1	0.83	0.64
11	0.82	1.06	1.29	1.18	0.93	0.66

Adaptation luminance values are simulated for MH lamp along with the effect of SLS 3 and shown below in **Table 7**.

iv. **Measurement of L_a when MH & all SLSs are on:**

Adaptation luminance values are simulated for MH lamp along with the effect of all SLSs using MATLAB software and listed below in **Table 8**.

Table 8: Adaptation luminance (in cd/m^2) when MH and all SLSs on

	A	B	C	D	E	F
1	1.63	1.87	2.78	2.77	1.42	0.86
2	1.75	2.53	2.75	2.9	1.43	0.84
3	2.02	2.65	2.9	3.31	1.43	0.91
4	2.31	3.23	3.04	3.31	1.75	0.9
5	2.24	3.11	2.93	3.02	1.82	1.2
6	2.11	2.85	2.92	2.98	2.06	1.03
7	1.83	2.13	2.48	2.32	2.5	1.21
8	1.44	1.82	2.11	1.66	2.26	1.05
9	1.31	1.56	2	1.7	1.74	0.86
10	1.1	1.48	1.87	1.64	1.62	0.69
11	1.08	1.5	1.97	2.07	1.95	0.73

C. For WLED Lamp:

For WLED lamp adaptation luminance is simulated in 4 different conditions:

- i. Measurement of L_a when WLED & SLS1 are on.
- ii. Measurement of L_a when WLED & SLS2 are on.

iii. Measurement of L_a when WLED & SLS 3 are on.

iv. Measurement of L_a when WLED & all SLSs are on.

i. Measurement of L_a when WLED & SLS1 are on:

Adaptation luminance values are simulated for WLED lamp along with the effect of SLS1 and shown below in **Table 9**.

Table 9: Adaptation luminance (in cd/m^2) when WLED and SLS1 are on

	A	B	C	D	E	F
1	2.00	2.30	2.37	1.83	1.20	0.95
2	2.46	2.80	2.63	1.96	1.35	0.96
3	2.71	2.91	2.64	2.13	1.52	1.18
4	2.95	3.11	2.69	2.25	1.83	1.26
5	2.88	3.01	2.42	1.86	1.64	1.53
6	2.75	3.13	2.47	2.03	1.57	1.27
7	2.71	2.91	2.27	1.94	1.77	1.10
8	2.13	2.32	2.06	1.58	1.55	0.86
9	2.09	2.10	1.87	1.71	1.48	0.90
10	1.26	1.61	1.74	1.60	1.46	0.87
11	1.09	1.30	1.67	1.78	1.80	0.82

ii. Measurement of L_a when WLED & SLS2 are on:

Adaptation luminance values are simulated (in cd/m^2) for WLED lamp along with the effect of SLS 2 and shown below in **Table 10**.

Table 10: Adaptation luminance (in cd/m^2) when WLED and SLS2 are on

	A	B	C	D	E	F
1	2.01	2.31	2.38	1.89	1.21	0.95
2	2.47	2.82	2.65	2.08	1.36	0.96
3	2.72	2.93	2.68	2.38	1.55	1.19
4	2.98	3.15	2.76	2.66	1.94	1.29
5	2.92	3.09	2.57	2.32	1.96	1.65
6	2.8	3.23	2.7	2.39	2.25	1.48
7	2.77	3.02	2.55	2.17	2.81	1.54
8	2.16	2.42	2.28	1.61	2.55	1.29
9	2.09	2.14	1.98	1.55	2.05	1.13
10	1.2	1.55	1.66	1.2	1.35	0.9
11	0.97	1.09	1.25	0.97	1.08	0.81

iii. Measurement of L_a when WLED & SLS3 are on:

Table 11: Adaptation luminance (in cd/m^2) when WLED and SLS3 are on

	A	B	C	D	E	F
1	2.02	2.34	2.44	1.97	1.42	1.13
2	2.48	2.84	2.70	2.10	1.58	1.14
3	2.72	2.94	2.70	2.24	1.66	1.28
4	2.96	3.13	2.73	2.32	1.89	1.30
5	2.89	3.02	2.45	1.89	1.68	1.53
6	2.74	3.12	2.47	2.01	1.59	1.27
7	2.69	2.87	2.25	1.90	1.74	1.09
8	2.08	2.25	1.98	1.47	1.46	0.85
9	2.01	1.98	1.70	1.48	1.32	0.89
10	1.13	1.41	1.43	1.13	1.01	0.86
11	0.90	0.98	1.12	0.93	0.93	0.78

Adaptation luminance values are simulated for WLED lamp along with the effect of SLS3 and listed below in **Table 11**.

iv. **Measurement of L_a when WLED & all SLSs are on:**

Adaptation luminance values are simulated for WLED lamp along with the effect of all SLSs using MATLAB software and listed below in **Table 12**.

Table 12: Adaptation luminance (in cd/m^2) when WLED and all SLSs are on

	A	B	C	D	E	F
1	2.02	2.35	2.45	2.03	1.43	1.13
2	2.49	2.86	2.73	2.22	1.59	1.15
3	2.74	2.97	2.74	2.48	1.70	1.29
4	3.00	3.19	2.81	2.74	2.00	1.33
5	2.95	3.12	2.62	2.37	2.00	1.67
6	2.84	3.28	2.74	2.47	2.27	1.49
7	2.81	3.08	2.61	2.24	2.86	1.55
8	2.23	2.51	2.38	1.74	2.66	1.30
9	2.19	2.28	2.17	1.80	2.21	1.14
10	1.33	1.75	1.97	1.67	1.80	0.91
11	1.16	1.42	1.80	1.82	1.95	0.85

D. For CWLED Lamp:

For CWLED lamp adaptation luminances are simulated in 4 different conditions:

i. Measurement of L_a when CWLED & SLS1 are on.

- ii. Measurement of L_a when CWLED & SLS2 are on.
- iii. Measurement of L_a when CWLED & SLS 3 are on.
- iv. Measurement of L_a when CWLED & all SLSs are on.

i. Measurement of L_a when CWLED & SLS1 are on:

Adaptation luminance values are simulated for CWLED lamp along with the effect of SLS1 and listed below in **Table 13**.

Table 13: Adaptation luminance (in cd/m^2) when CWLED and SLS1 are on

	A	B	C	D	E	F
1	2.5	2.8	2.82	2.01	1.34	1.08
2	2.82	3.34	2.84	2.1	1.43	1.12
3	3.15	3.54	2.74	2.34	1.61	1.25
4	3.35	3.68	2.89	2.36	1.62	1.29
5	3.2	3.38	2.6	1.96	1.7	1.57
6	3.12	3.34	2.54	2.19	1.61	1.37
7	2.73	3.09	2.41	2	1.85	1.12
8	2.36	2.58	2.24	1.67	1.55	0.96
9	1.69	1.9	2.05	1.84	1.37	0.9
10	1.43	1.76	1.79	1.71	1.48	0.86
11	1.16	1.38	1.68	1.81	1.78	0.84

i. Measurement of L_a when CWLED & SLS2 are on:

Adaptation luminance values are simulated for CWLED lamp along with the effect of SLS2 using MATLAB software and listed below in **Table 14**.

ii. Measurement of L_a when CWLED & SLS3 are on:

Adaptation luminance values are simulated for CWLED lamp along with the effect of SLS3 and listed below in **Table 15**.

2. Set 2: MLS & WWSLS

A. For HPSV Lamp:

Table 14: Adaptation luminance (in cd/m^2) when CWLED and SLS2 are on

	A	B	C	D	E	F
1	2.51	2.81	2.83	2.07	1.35	1.08
2	2.83	3.36	2.86	2.22	1.44	1.12
3	3.16	3.56	2.78	2.59	1.64	1.26
4	3.38	3.72	2.96	2.76	1.73	1.32
5	3.24	3.46	2.75	2.42	2.02	1.69
6	3.17	3.44	2.77	2.55	2.29	1.58
7	2.79	3.2	2.68	2.23	2.89	1.56
8	2.69	1.68	2.46	1.7	2.55	1.39
9	1.69	1.93	2.16	1.68	1.94	1.13
10	1.37	1.7	1.71	1.31	1.37	0.89
11	1.04	1.17	1.26	1	1.06	0.83

Table 15: Adaptation luminance (in cd/m^2) when CWLED and SLS3 are on

	A	B	C	D	E	F
1	2.52	2.84	2.89	2.15	1.56	1.26
2	2.84	3.38	2.91	2.24	1.66	1.3
3	3.16	3.57	2.8	2.44	1.75	1.35
4	3.36	3.7	2.93	2.42	1.68	1.33
5	3.21	3.39	2.63	1.99	1.74	1.57
6	3.11	3.33	2.54	2.17	1.63	1.37
7	2.71	3.05	2.38	1.96	1.82	1.11
8	2.31	2.51	2.16	1.56	1.46	0.95
9	1.61	1.78	1.88	1.61	1.21	0.89
10	1.3	1.57	1.48	1.24	1.03	0.85
11	0.97	1.06	1.12	0.96	0.91	0.8

Table 16: Adaptation luminance (in cd/m^2) when HPSV and all SLSs are on

	A	B	C	D	E	F
1	1.79	2.12	2.17	1.54	1.01	0.62
2	1.54	1.96	1.96	1.26	0.88	0.76
3	1.56	2.10	1.84	1.40	0.91	0.62
4	1.54	2.23	2.05	1.46	0.95	0.57
5	1.67	2.19	2.04	1.58	1.22	0.63
6	1.74	2.22	2.13	1.78	1.62	0.71
7	1.76	2.56	2.61	2.12	2.17	0.61
8	1.61	2.34	2.69	2.03	2.29	0.62
9	1.26	1.81	2.26	1.74	1.88	0.64
10	1.05	1.56	1.99	1.76	1.65	0.52
11	1.02	1.42	2.32	1.99	1.82	0.44

For HPSV lamp adaptation luminances are simulated for only one condition as shown in Table 4.1. Adaptation luminance values are simulated for HPSV lamp along with the effect of all three SLSs using MATLAB software and shown in **Table 16**.

B. FOR MH Lamp:

Adaptation luminance values are simulated for MH lamp along with the effect of all three SLSs using MATLAB software and shown in **Table 17**.

Table 17: Adaptation luminance (in cd/m^2) when MH and all SLS on

	A	B	C	D	E	F
1	0.94	1.76	2.33	2.20	1.13	0.59
2	1.02	1.48	2.05	1.65	0.91	0.71
3	1.11	1.48	1.82	1.78	0.92	0.55
4	1.10	1.56	1.86	1.83	1.01	0.50
5	1.11	1.62	1.83	1.94	1.24	0.53
6	1.25	1.68	1.91	2.08	1.66	0.59
7	1.12	1.77	2.09	2.39	2.26	0.53
8	1.00	1.49	2.00	2.10	2.28	0.50
9	0.96	1.32	1.74	1.74	1.79	0.59
10	0.80	1.19	1.62	1.66	1.57	0.45
11	0.82	1.21	1.87	1.85	1.77	0.38

C. For WLED Lamp:

Adaptation luminance values are simulated for WLED lamp along with the effect of all three SLSs using MATLAB software and shown in **Table 18**.

Table 18: Adaptation luminance (in cd/m^2) when WLED and all SLS are on

	A	B	C	D	E	F
1	2.64	2.80	2.63	2.12	1.67	1.02
2	2.58	2.78	2.55	1.87	1.55	1.40
3	2.66	2.89	2.52	2.32	1.74	1.27
4	2.58	2.92	2.66	2.32	1.87	1.26
5	2.59	2.70	2.39	2.31	2.09	1.34
6	2.67	2.52	2.40	2.35	2.37	1.42
7	2.33	2.75	2.65	2.50	2.90	1.24
8	2.07	2.48	2.68	2.27	2.79	1.04
9	2.01	2.06	2.36	1.97	2.22	0.98
10	1.30	1.66	1.99	1.90	1.95	0.84
11	1.22	1.43	1.91	2.05	2.01	0.63

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