CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF ELECTRICAL ENGINEERING

DEPARTMENT OF ELECTRICAL POWER ENGINEERING

MASTER THESIS

THE APPLICATION OF BIO-DYNAMIC LUMINARIES FOR ROAD LIGHTING

By: Bharath Chandran

Supervisor: Ing. Marek Bálský, Ph.D.

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MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Chandran Bharath** Personal ID number: **481002**

Faculty / Institute: **Faculty of Electrical Engineering**

Department / Institute: **Department of Electrical Power Engineering**

Study program: **Electrical Engineering, Power Engineering and Management**

Specialisation: **Electrical Power Engineering**

II. Master's thesis details

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Možnosti užití tunable white svítidel pro osvětlení komunikací

Guidelines:

1) Summarize the technical standards and guidelines related to biodynamic road lighting.
2) Analyze the influence of biodynamic road lighting on traffic drivers and the environment.
3) Propose the guidelines of biodynamic road lighting design according to technical standards and the infuence on environment.

Bibliography / sources:

[1] European Standard EN 13201: Road lighting
[2] EUR 29631 EN Revision of the EU Green Public Procurement Criteria for Road Lighting and traffic signals
[3] DILAURA, D. A KOL. IES Lighting Handbook. 10. ed., Illuminating engineering society, 2010,1328 pages, ISBN 978-0-87995-241-9

Name and workplace of master's thesis supervisor:

Ing. Marek Bálský, Ph.D., Department of Electrical Power Engineering, FEE

Name and workplace of second master's thesis supervisor or consultant:

Date of master's thesis assignment: **13.02.2020** Deadline for master's thesis submission: **22.05.2020**

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Ing. Marek Bálský, Ph.D. Supervisor's signature	Head of department's signature	prof. Mgr. Petr Páta, Ph.D. Dean's signature

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DECLARATION

I hereby declare that this master's thesis is the product of my own independent work and that I have clearly stated all information sources used in the thesis according to Methodological Instruction No. 1/2009 – "On maintaining ethical principles when working on a university final project, CTU in Prague".

Date Signature

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ABSTRACT

The thesis deals with the application of bio-dynamic luminaries for road lighting. The work is divided into several parts. The first part encompasses the theoretical aspects of present road lighting system explaining the currents trends, the technical aspects, the concepts relating to circadian rhythm, the bio-dynamic lighting and so on. The second part covers the literature review related to the environmental concerns based on the current road lighting system describing aspects such as light pollution and its effect on the environment. Furthermore, the part describes the control strategies to curtail light pollution covering aspects like the need for the quantification of blue light, the effect of spectral colour variation and so on. The third part explains the influence of bio-dynamic road lighting on the Motorists, Pedestrians and the Environment, with its capability to vary the correlated colour temperature. The last part comprises of the proposal of guidelines for the implementation of the bio-dynamic road lighting system in accordance with the technical standards and its influence on the environment.

ABSTRAKT

Diplomová práce se zabývá aplikací biodynamických svítidel na osvětlení silnic. Práce je rozdělena do několika částí. První část zahrnuje teoretické aspekty současného systému osvětlení silnic vysvětlující trendy proudů, technické aspekty, pojmy týkající se cirkadiánního rytmu, bio dynamického osvětlení atd. Druhá část se zabývá přezkumem literatury týkající se environmentálních problémů na základě současného systému osvětlení silnic popisujícího aspekty, jako je znečištění světla a jeho vliv na životní prostředí. Tato část dále popisuje kontrolní strategie omezující znečištění světla, které se týkají aspektů, jako je potřeba kvantifikace modrého světla, účinek spektrální barevné variace atd. Třetí část vysvětluje vliv bio-dynamického osvětlení vozovky na motoristy, chodce a životní prostředí s možností změny korelované barevné teploty. Poslední část obsahuje návrh pokynů pro implementaci bio dynamického systému osvětlení silnic v souladu s technickými normami a jeho vliv na životní prostředí.

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LIST OF ABBREVIATIONS

LED	Light emitting diode
HID	High-intensity discharge
MH	Metal Halide
HPS	High pressure sodium
HPM	High pressure mercury
LPS	Low pressure sodium
CFL	Compact fluorescent lamp
SI	Système international
LSF	Lamp survival factor
LLMF	Lamp lumen maintenance factor
CRI	Colour rendering index
CCT	Correlated colour temperature
EN	European Norms
CIE	Commission Internationale de l'Eclairage
TR	Technical report
RGB	Red-Green-Blue
ipRGCs	Intrinsically photosensitive retinal ganglion cells
CAR	Cortisol awakening response
IDA	International Darksky association
GR	Glare rating
UGR	Unified glare rating
TI	Threshold increment
ALAN	Artificial light at night
LOR	Light output ratio
ULOR	Upward light output ratio
IP	Ingress protection
IK	Impact protection
ITT	Invitations to tender

LIST OF SYMBOLS

η_{inst}	Luminous Efficacy of the installation	(lm/W)
C_L	Correction factor	(unitless)
F_M	Maintenance factor	(unitless)
F_{LLM}	Lamp maintenance factor	(unitless)
F_{LM}	Luminaire maintenance factor	(unitless)
U	Utilance	(%)
R_{LO}	Optical Efficiency	(%)
η_{ls}	Luminous efficacy of the light source	(lm/W)
η_p	Luminous efficacy of the luminaire	(lm/W)
U_o	Luminous Uniformity	(unitless)
L_{min}	Minimum Luminance	(cd/m^2)
L_{avg}	Average Luminance	(cd/m^2)
E_{min}	Minimum Illuminance	(lx)
E_{max}	Maximum Illuminance	(lx)
λ	Wavelength	(nm)
$V_1(\lambda)$	Photopic Luminous Efficacy	(cd/W)
$V_2(\lambda)$	Scotopic Luminous Efficacy	(cd/W)
E_v	Vertical Illuminance	(lx)
E_{havg}	Average Horizontal Illuminance	(lx)
U_{0h}	Horizontal Illuminance Uniformity	(unitless)
E_{v1}	Vertical Illuminance (street side)	(lx)
E_{v2}	Vertical Illuminance (opposite side of street)	(lx)
L_i	Luminance of the glare source	(cd/m^2)
L_u	Average background luminance	(cd/m^2)
ω_i	Solid angle	(˚)
P_i	Position index (Guth's Index)	(unitless)
L_{vl}	Veil luminance of lighting system	(cd/m^2)
L_{ve}	Veil luminance of environment	(cd/m^2)
L_{ad}	Adaptive Luminance	(cd/m^2)
R_{ULO}	Ratio of upward light output	(%)
B	Blue light content	(W)
G	Spectral G-index	(unitless)
L	Luminance	(lm)
$E(\lambda)$	Luminosity function	

1. INTRODUCTION

Although the story of the creation of the artificial light bulb began at the beginning of the 18th century, it was on January 27th of the year 1880, an American inventor, and businessman named Mr. Thomas Alva Edison patented the invention of the first pragmatic and commercial incandescent light bulb. It was a revolutionary and life-changing event that improved the life quality of the people to a greater extent as they no longer had to entirely rely on natural sunlight or candles for lightening their society. Later, a multitudinous amount of startling discoveries happened in the field of lighting technology as the public started to focus on the efficiency of lighting. The lamp technologies, including compact fluorescent lamps, mercury vapour lamps, high and low-pressure sodium discharge lamps and Light-emitting diodes, came into existence [56].

In the year 1962, Nick Holonyak Jr. invented the first commercial light-emitting diode (LED) in the visible spectrum of red colour. Numerous developments on LED have materialized after the breakout of the first of its kind. This study will mainly be focusing on possible future development on improving the practicality of LEDs in the road lighting system with the utmost attentiveness on the safety of society [56].

2. SCOPE & OBJECTIVES

The prominence of the LED lighting system is upsurging with each passing day, and the practicality of its development in road lighting is far from over. This study will focus on an idea which utilizes the colour tunable aspect of LEDs technology in the road lighting system, having the potential to improve the life quality of the people as well as the environment as a whole. The proposed technology is called as the bio-dynamic lighting system, and it has been getting attention in case of the indoor lighting scenarios in some parts of the world.

The thesis is centralized on the application of bio-dynamic road lighting system explaining the technical aspects, the impact on traffic drivers and environment and the development of the guidelines based on the impact on society.

3. CURRENT TRENDS IN ROAD LIGHTING SYSTEM

Road lighting plays a prominent role in the safety of our society. An excellent road lighting system facilitates a quality traffic flow, ensuring better visibility for the pedestrians and the drivers for viewing objects at night. It significantly reduces road accidents post dusk. Besides, it could improve the aesthetic elements of the environment by making it visually pleasing. The standard of road lighting system depends on various aspects like the uniformity of illuminance, glare and skyglow. These attributes of lighting could make or break the quality of illuminance.

The main lamp technologies used in road lighting these days are light-emitting diodes (LED), high-intensity discharge lighting (HID) comprising of metal halides (MH), high-pressure sodium (HPS) and high-pressure mercury (HPM), low-pressure sodium (LPS) and compact fluorescent lamps (CFL). In Europe, the wide use of high-intensity discharge lighting technology has reduced significantly over the years. The sale of high-pressure mercury lamps came to an end in April 2015 as a result of their elimination from the European market as per the regulation 245/2009 of the European Commission [22]. All these factors led to the mass emergence of LEDs in the European market. Currently, the LEDs are receiving much acceptance, and they are on a surge to take over the road lighting market.

4. TECHNICAL ASPECTS OF ROAD LIGHTING

The technical aspects for road lighting are defined under different types of lighting systems comprising the LEDs, low-pressure sodium, fluorescent lamps and high-intensity discharge lamps (HID) which includes high-pressure sodium (HPS), metal halides (MH) and high-pressure mercury (HPM).

The following parameters are considered while selecting a lamp for road lighting,

4.1. Luminance

Luminance is the intensity of light passes through, emitted from or reflected from a surface within a solid angle. It indicates the luminous power which can be perceived by a human eye. The SI unit of luminance is candela (cd).

4.2. Illuminance

Illuminance is the measurement of the quantity of light illuminating and spreading over a particular area. The SI unit if Illuminance is lux (lx). It describes the brightness perception of the human eye over a particular area.

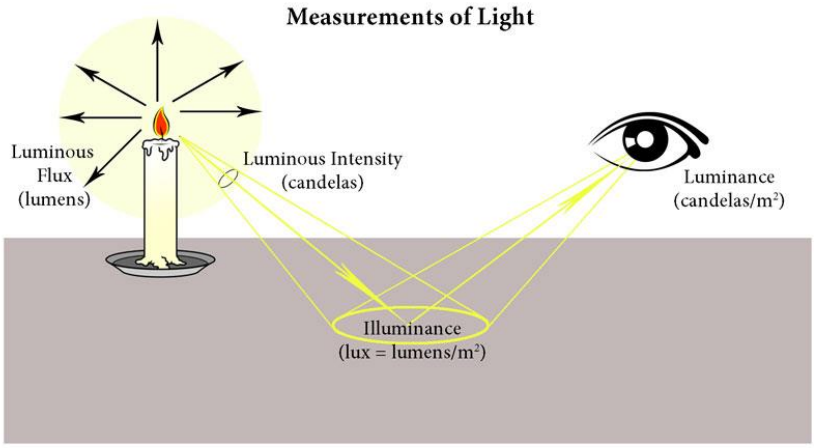


Figure 1. Luminance and Illuminance

4.3. Luminous Efficacy

Luminous Efficacy (η) is the ratio of the light output of the lamp or luminous flux and the total electric power consumption of the lamp. The luminous efficacy can be defined at different levels: considering a light source, a luminaire where the light source is fitted or an installation as a whole.

The EN 13201-5:2016 defined the equation of luminous efficacy as [22],

$$\eta_{inst} = C_L \times F_M \times U \times R_{LO} \times \eta_{ls} \times \eta_p$$

- η_{inst} - Luminous Efficacy of the installation in lm/W

- C_L – Correction factor if the basis of design is in luminance or hemispherical illuminance instead of illuminance.
- F_M – Overall maintenance factor of the installation (F_{LM} x F_{LLM})

  F_{LLM} – Lamp maintenance factor (combination),

  F_{LM}- Luminaire maintenance factor
- U – Utilance (the percentage of light output reaching the intended zone)
- R_{LO}- Optical efficiency(the percentage of the light output from the light source leaving the luminaire)
- η_{ls}- Luminous Efficacy of the light source (lm/W)
- η_P- Luminous Efficacy of the luminaire (including the power loss in the control gear) (lm/W)

4.4. Luminous Uniformity

The ratio between the minimum illuminance level to the average illuminance level describes the Luminous Uniformity [55]. The range of value varies between 0 and 1, with 1 signifying maximum uniformity in the distribution of light. The equation is a follows,

$$U_0 = \frac{L_{min}}{L_{avg}}$$

- U_0 - Luminous Uniformity (unitless)
- L_{min}- Minimum luminance (cd/m^2)
- L_{avg} - Average luminance (cd/m^2)

4.5. Lamp survival factor

Lamp survival factor (LSF) is defined as the lamps surviving after a definite period. This factor varies with the lamps. Except for LED, all the other light sources can be applied to LSF directly. LSF is expressed in decimals like 0.90 or 0.80 for a particular period of time. In the case of LED technology, the term Cz is used instead of LSF. C10 at 60000 hours signifies that 10 % of LED lights have failed after a usage duration of 60000 hours [22].

4.6. Lamp lumen maintenance factor

Lamp lumen maintenance factor (LLMF) depends on the decrease in the light output of a lamp considering the future. It is as the amount of light output received from a lamp at a specific time in the future. All the lamps except for LEDs directly follows this LLMF calculation. In the case of LED, the LLMF is modified to LxBy. For example, L70B10 at 50000 hours signifies that around 10 % of the LEDs will lose 70 % of its light output after lighting for 50000 hours [22].

4.7. Colour rendering index

The colour rendering index (CRI) is the measurement of the ability of a light source to exhibit the colour of an object accurately. It determines the quality of the lamp and is expressed in a percentage scale. Typically, a light source with CRI higher than 80 is considered as sufficient in most conditions.

The requirement of CRI from a light source depends on the type of application. For example, a commercial building will require a light source of CRI 80. In contrast, a retail textile shop will require a higher CRI valued light source or around 90 for revealing the colour of clothes for pleasing the customers accurately. The standard lamps of CRI higher than 60 are enough for road lighting as they do not demand much aesthetics. Same as in the case of industrial lighting, where sometimes a CRI of even 40 is considered sufficient. Normal outdoor lighting doesn’t require a significant amount of CRI, but landscape lighting may require high CRI of more than 90 [57].

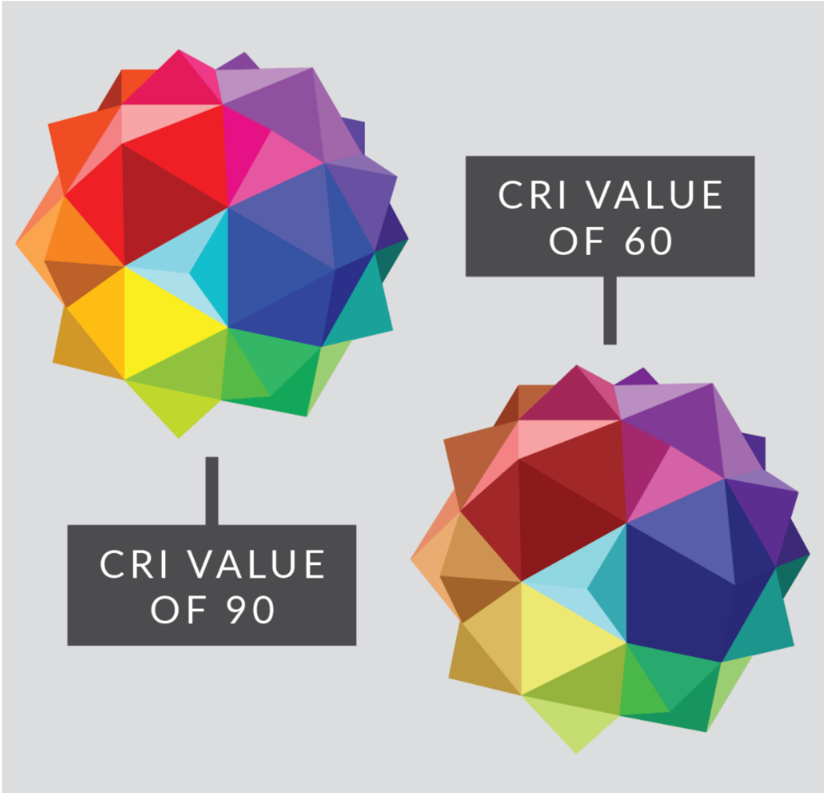


Figure 2. Variation in colour rendering index [1]

4.8. Correlated colour temperature (CCT)

The artificial light sources such as LEDs are labelled with a CCT value, measured in the kelvin scale. The CCT value conveys the tone of white light that the lamp emits. The temperature could vary from 1700 K (warm white) to 7500 K (cool white). In the case of LED, a CCT of between 2000 K to 3500 K is considered as a warm white LED, of that above 3500 K until 5100 K is considered as a neutral white LED and between 5100 K and 7500 K value are considered as cool white LED.

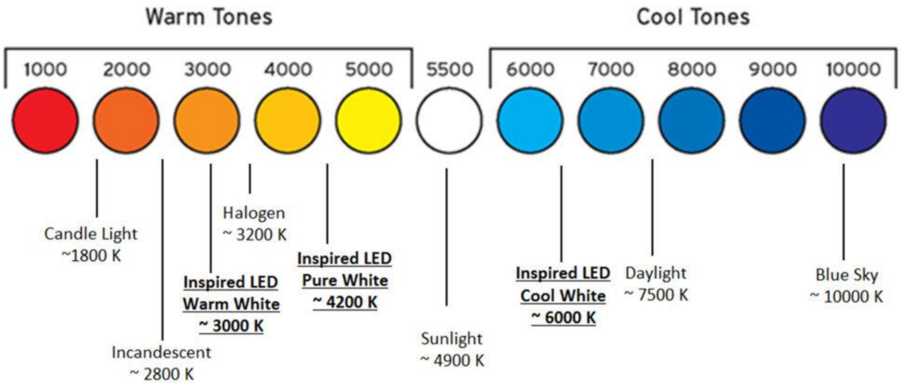


Figure 3. Colour temperature in kelvin scale [2]

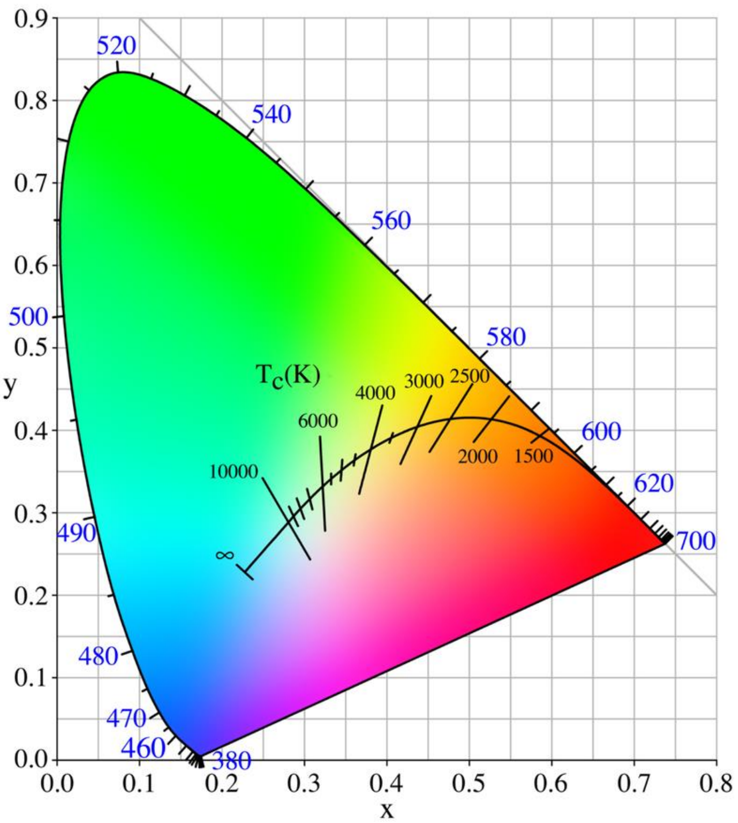


Figure 4. Chromaticity diagram [35]

The chromaticity diagram portrays a graph indicating all possible colours in the visible spectrum. Each colour is represented by a pair of numerical coordinates called chromaticity coordinates. The points on the outer curved border of the diagram represent pure colours of the visible spectrum, and the colours inside are the mixtures of pure colours. The black line in the graph indicates the spectral colour emitted by the black body with changes in temperature (T_C (K)), where is kelvin [35].

4.9. Safety Criteria

4.9.1. Ingress Protection

The ingress protection code, generally known as IP code, systematize the degree of resistance of the luminaire's mechanical casing against the intrusion of dust and moisture. It also determines the maintenance of a luminaire, according to CIE 154:2003. The IP rating is mentioned as a two-digit code in which the first digit signifies the protection against the moving parts and hazardous contact to electrical conductors and the second digit indicates the degree of protection against the exposure to moisture [34].

According to Ecodesign regulation EC/245/2009, IP-65 should be a benchmark for all the M class roads (M1-M6) and IP-5x, where x should be a number indicating the degree of protection against moisture, for all the C and P class roads.

4.9.2. Impact Protection

The European standard EN 62262 defines the degree of protection provided by the mechanical casing of electrical equipment against mechanical impacts. It is expressed as IK rating, which signifies the resistance to kinetic energy impacts [34]. The IK rating is described on a scale of 0 to 10, with IK10 having the most resistance.

4.9.3. Over-voltage Protection

Most of the manufacturers of lighting technology design their products to withstand a transient voltage surge of 2 kV to 4 kV. It is not enough in this day and age, considering the demand for the longevity of electrical equipment. In contrast to the conventional lighting system, LEDs are generally designed for low voltage applications, and their control gears are prone to actual overvoltage caused damages. It is necessary to provide adequate overvoltage protection in LED-based luminaries.

A lightning strike could induce a transient voltage spike of up to 10 kV on the lighting system, which could quickly destroy the system considering the current design tolerance.

4.9.4. Control Gear Criteria

The control gear regulates the electrical operation of a lighting system. It has components which control the transformation of voltages and performs power factor correction. It is considered as the weakest point in the lighting system when it comes to longevity. The core criteria in TR 4.0 [22] is to implement high-quality control gears with a failure rate of less than 0.2% per 1000 hours.

5. LIGHT EMITTING DIODE (LED)

The light-emitting diode is a semiconductor device that emits light under the process of electroluminescence. Electroluminescence is a phenomenon eventuate on a semiconductor when an electric current is passed through it causing the recombination of electrons with holes leading to the emission of light energy.

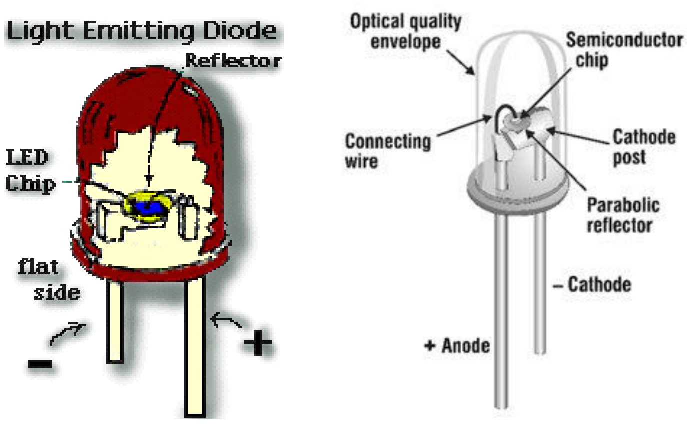


Figure 5. The basic structure of a light-emitting diode [3]

LED lights can be classified based on colour temperatures; warm white and cool white. The colour temperature of the warm white variant is 3000 K, and that of cool white is 6000 K.

The colour temperature of natural daylight is close to 5000 K making the warm white led (3000 K) a more suitable replacement to daylight compared to cool white led (6000 K).

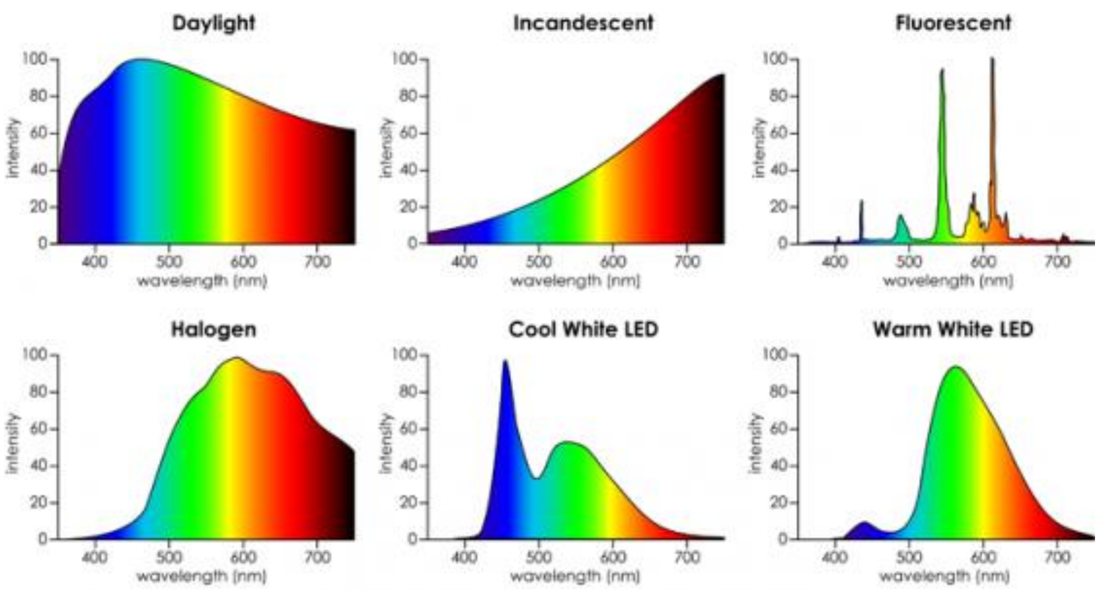


Figure 6. The spectrum of various light sources [4]

5.1. Merits of LED

The LEDs are distinct from other lighting technologies in case of function. Their advantage over the conventional light sources is enormous. The benefits are as follows:

1. The lifetime of LED is significantly higher than its competitors. The average lifetime of an LED is as high as 50000 hours to 100000 hours. The reason for the high life could be because of the absence of moving parts as found in the

conventional lighting systems. Besides, LED will not get burned out; instead, it will only get affected by lumen depreciation with time.

2. The use of electronic ballast in LED as opposed to conventional magnetic ballast can improve the power controlling aspect of the lighting system. They also enhance the efficiency of the lamp.
3. The luminous efficacy of LED is independent of the rated power of the lamp, whereas, in all other light sources, the efficiency increases with an increase in the power rating. The efficiency of the low power rated conventional lighting sources are considerably less than the efficiency of a low power rated LED.
4. Compared to other light sources which emit light omnidirectionally, the LEDs emit in a unidirectional manner. This feature is advantageous in the case of energy consumption and makes it able to use energy more efficiently. This aspect of LED makes it extremely suitable for road lighting.
5. The maintenance cost of LED is much lower when compared with other light sources.
6. Unlike the conventional light sources, the LEDs are capable of dimming. As light output of LEDs are directly in proportion with the current, this could be considered as an energy saving mechanism as well as a light pollution control strategy.

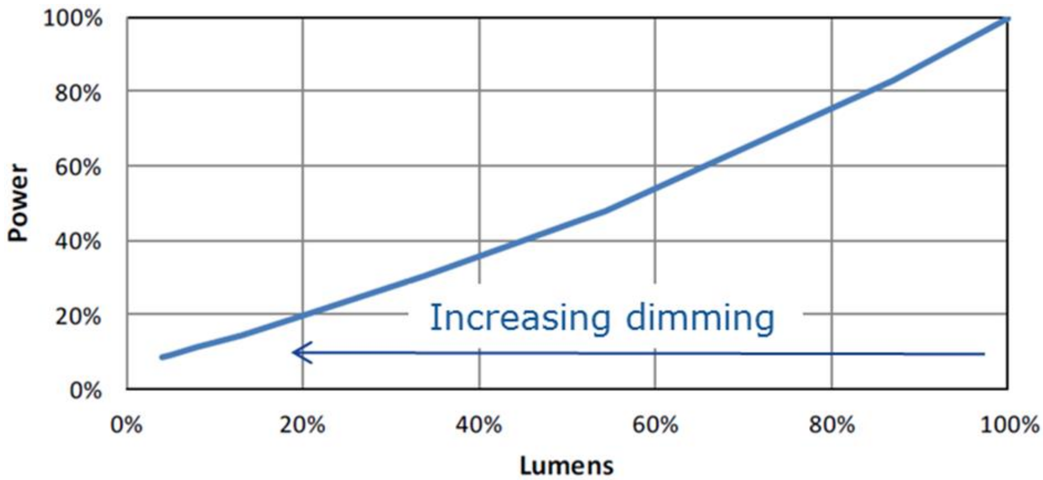


Figure 7. Power consumption vs Dimming of luminous output [22]

5.2. Demerits of LED

Although the LEDs are significantly advantageous compared to conventional counterparts, there are some demerits which need to be addressed. They are :

1. The spectrum of light emitted from the standard white LED has a peak in the blue region of visible light, which could be harmful to the human eye over a prolonged period of exposure. Fortunately, the effect of this drawback can be diminished by adjusting the colour temperature of LEDs that will be explained further in this study.
2. Exposure to the blue light from an LED could suppress the production of melatonin in our body. Melatonin is the hormone that controls the circadian rhythm of a human being. Disruption of the natural production of melatonin could cause sleeplessness followed by medical conditions like insomnia
3. Compared to conventional lights, the initial cost of an LED is higher.
4. The LEDs does not produce much heat as compared to other conventional lighting systems due to the high efficiency. However, it requires a proper heat dissipation mechanism, like a heat sink, in order to maintain efficiency over time. The figure 8 describes the variation in the light output of 6W LED (without heat sink) with an increase in junction temperature [36].

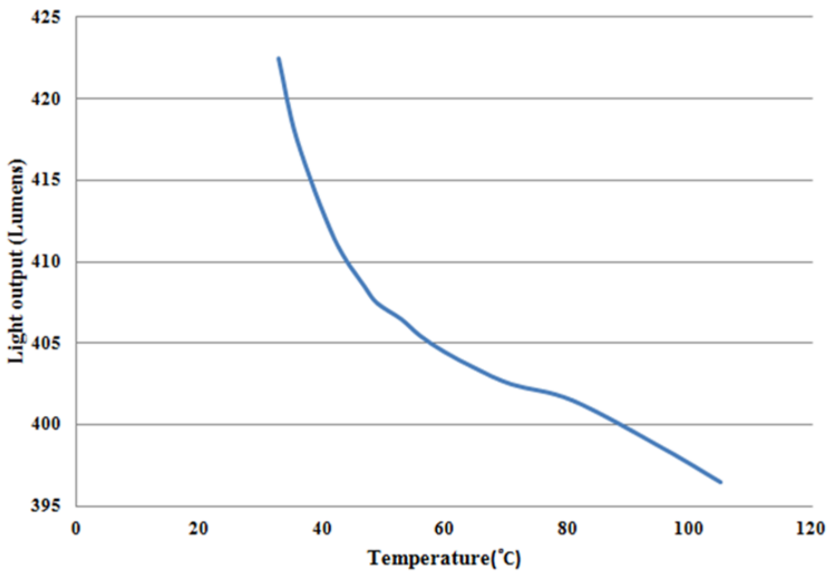


Figure 8. Lumen output vs Junction temperature [36]

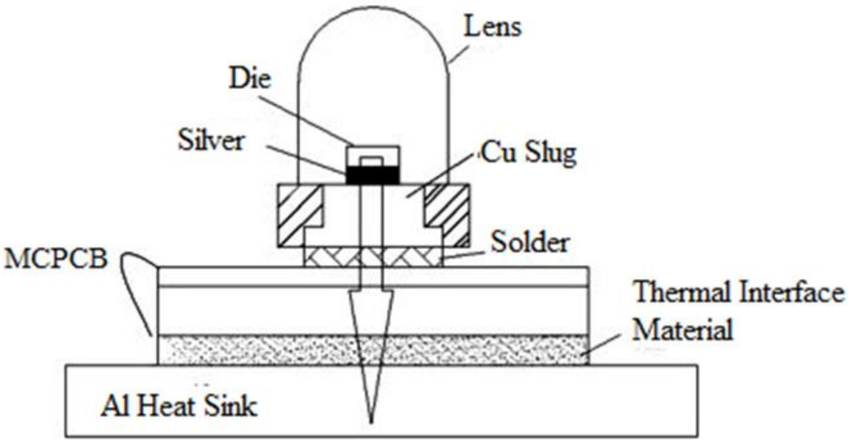


Figure 9. An LED with heat sink [36]

5. The replacement of the LED lighting system can prove arduous. Unlike conventional lighting systems, the LEDs are integrated with the heat sink and driver electronics. A failure in any of these parts could affect the entire system. The longevity of an LED light source is a proven factor, but it will become irrelevant if the integrated component fails to keep up the quality.
6. The dimming comes with a caveat.

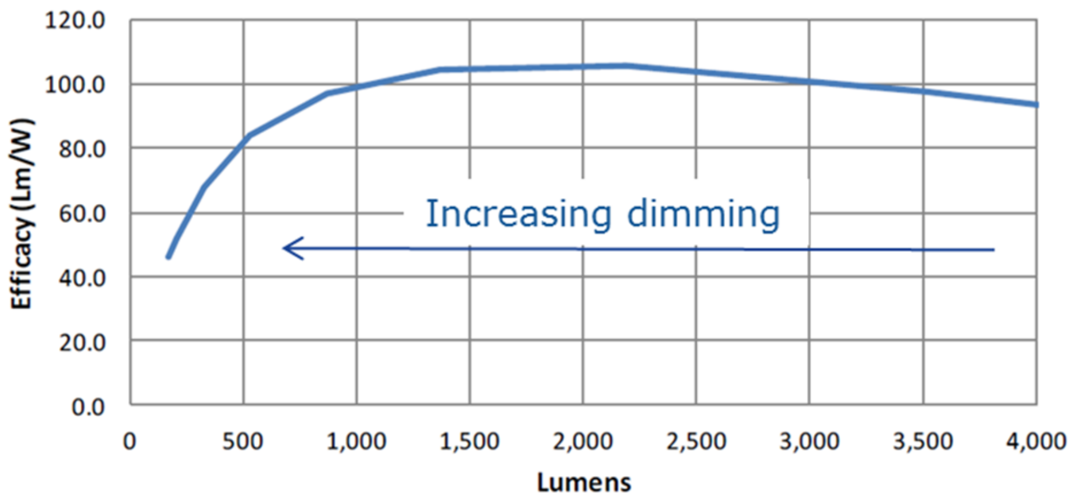


Figure 10. Luminous efficacy vs Dimming of luminous output [22]

The efficacy of the luminaire drastically reduces with increase in dimming beyond a particular point as the low power consumption of drivers becomes more pronounced [22].

6. LED's EFFICIENCY AS A FUNCTION OF CCT

The dip in the luminous efficacy with lowering the CCT is a point of concern for the developers and environmentalists as the low CCT lighting have its share of advantages over high CCT lighting considering the blue light content factor. The 4000 K luminaire has higher efficiency than the 3000 K counterpart.

In order to produce white light from an LED, a semiconductor chip capable of emitting blue light is generally used as the blue light of wavelength 460 nm has more energy than the long wavelength red light. The emitted blue light gets converted to different colours, including long-wavelength spectral lights like green and red, using a converter or phosphor, and then all the necessary produced colours are mixed together to produce white light. The process is known as down conversion. The conversion process generates heat loss caused by the difference in the energy level between the shorter wavelength lights and longer wavelength lights, which affects the luminous efficacy of the luminaire. In order to produce a warm colour of CCT 3000 K, a considerable amount of long-wavelength red light conversion is necessary, dealing with greater heat losses compared to that caused by the conversion for generating 4000 K light. The requirement of conversion to red light decreases with an increase in CCT [47].

7. SPECTRAL SENSITIVITY OF HUMAN EYE

The human eye is sensitive to lights within the wavelength of the visible spectrum. The visible spectrum of light can be considered as the lights with the wavelength in between 380 nm to 780 nm. The spectrum preceding the visible spectrum is the Ultraviolet spectrum, and the spectrum succeeding the visible spectrum is the Infrared spectrum. The Spectral Sensitivity of light is defined as the relative efficiency of light at different wavelengths. The Human eye is comprised of mainly three photoreceptors, the rods, the cones, and intrinsically photosensitive retinal ganglion cells.

The rods are photoreceptors in the retina of the eye that provide vision during the night or otherwise can be called scotopic vision. They are more sensitive than cones and are responsible for the entire night vision whereas, contributing near to nothing to the colour vision [38].

The cones in the retina become active during day time, described as a photopic vision. These cells can differentiate the colours in the visible spectrum. They are less sensitive to light than rod cells but allows colour perception. They are generally classified into three types as S-cones, M-cones and L-cones with each differ in photopsin. Each of them responds distinctively to the visible wavelength of lights comprising of short, medium and long-wavelength light [38]. The responsiveness of three types of cones are indicated in figure 11, with S-cones absorbs short-wavelength lights of 445 nm (blue), M-cones absorbs medium wavelength lights of 535 nm (green), and lastly, the L-cones absorbs the long-wavelength lights of 575 nm (red). The cones mix the basic red, green and blue (RGB) in the visible spectrum to produce millions of colours.

The third photoreceptor, known as the intrinsically photosensitive retinal ganglion cells (ipRGCs) acquires the data of light intensity from the environment. It sends it to the brain, which in turn determines our cognitive performance, sleep cycle and the stability of the circadian rhythm. The associated retinal ganglion cells (RGC) contains a pigment Melanopsin, which is intrinsically photosensitive and direct a non-visual light perception system responsible for the circadian photoentrainment in an organism [39]. The activation of melanopsin by the artificial or natural daylight plays a prominent role in the regulation of the circadian system in the human being. In the morning hours, the activated melanopsin sends signals to the pineal gland in order to suppress the production of melatonin and encourage the production of cortisol, increasing the alertness in human beings. Nevertheless, its untimely activation could disrupt the circadian rhythm, for example, exposure to artificial light with short wavelength content at post evening hours could negatively impact the sleep cycle of an individual [43].

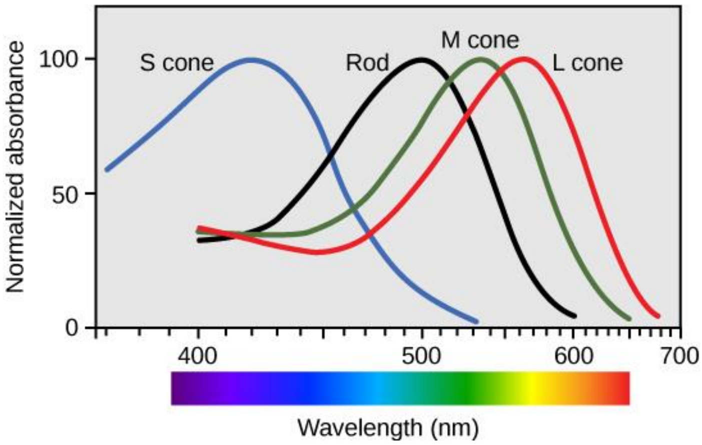


Figure 11. The response of cone and rod cells [5]

Table 1. The luminous efficacy of human retina based on different wavelengths of light [23]

Wavelength, λ (nm)	Photopic Luminous Efficiency, $V_1(\lambda)$ (lm/W)	Scotopic Luminous Efficiency, $V_2\lambda$ (lm/W)
380	0.000039	0.000589
390	0.00012	0.002209
390	0.00012	0.002209
400	0.000396	0.00929
410	0.00121	0.03484
420	0.004	0.0966
430	0.0116	0.1998
440	0.023	0.3281
450	0.038	0.455
460	0.06	0.567
470	0.09098	0.676
480	0.13902	0.793
490	0.20802	0.904
500	0.323	0.982
507	0.44431	1
510	0.503	0.997
520	0.71	0.935
530	0.862	0.811
540	0.954	0.655
550	0.99495	0.481
555	1	0.402
560	0.995	0.3288
570	0.952	0.2076
580	0.87	0.1212
590	0.757	0.0655
600	0.631	0.03315
610	0.503	0.01593
620	0.381	0.00737

630	0.265	0.003335
640	0.175	0.001497
650	0.107	0.000677
660	0.061	0.000313
670	0.032	0.000148
680	0.017	0.000072
690	0.00821	0.000035
700	0.004102	0.000018
710	0.002091	0.000009
720	0.001047	0.000005
730	0.00052	0.000003
740	0.000249	0.000001
750	0.00012	0.000001
760	0.00006	0
770	0.00003	0

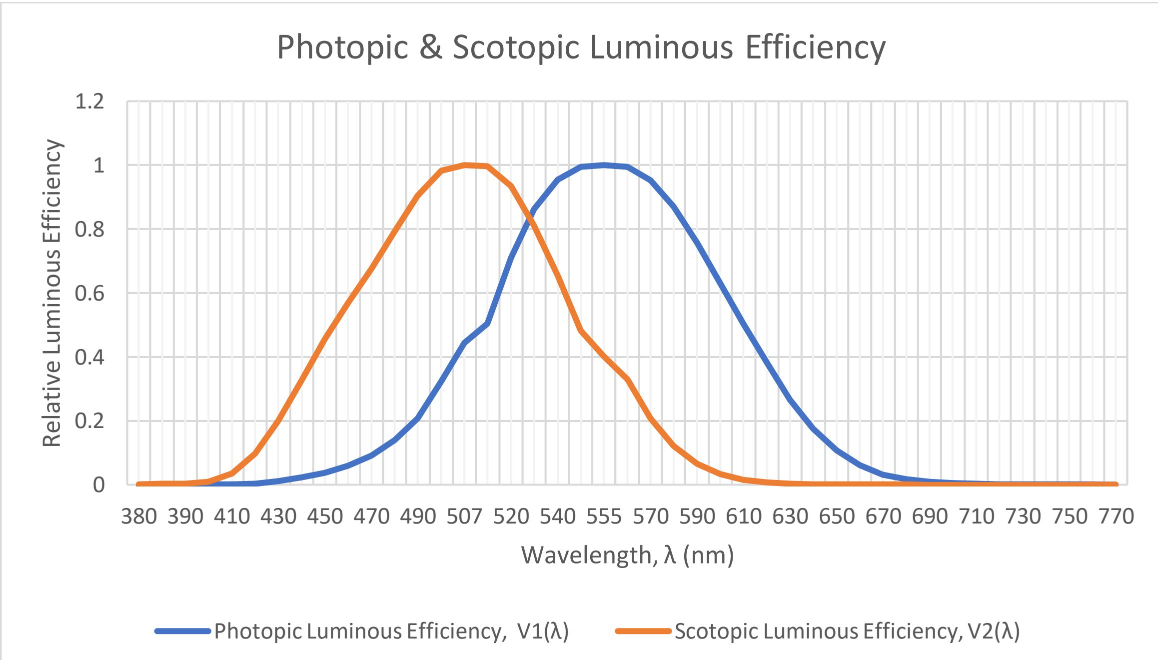


Figure 12. The wavelength of light vs Photopic & Scotopic luminous efficiency

During day time, our eye is more sensitive to lights of 555 nm (yellow) wavelength, and at night time, the scotopic vision makes our eye more sensitive to a wavelength of 507 nm (blue-green) approximately.

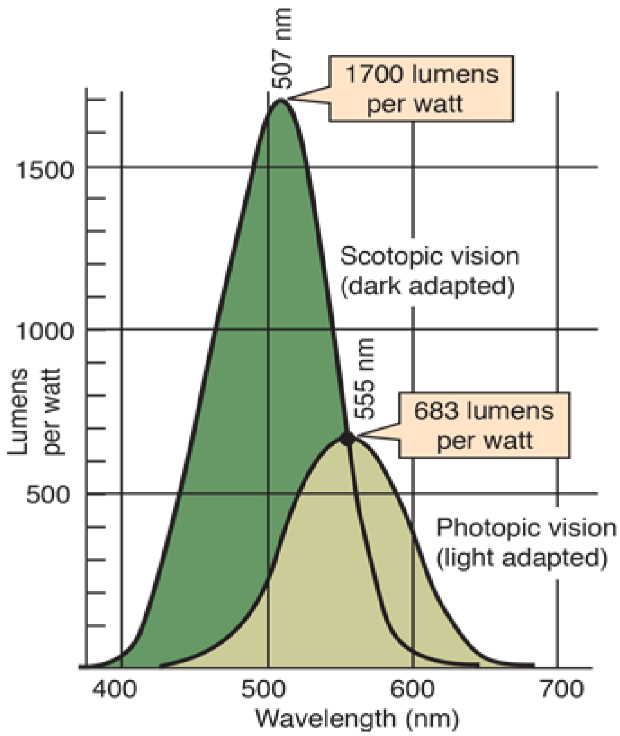


Figure 13. Scotopic and Photopic vision [23]

8. CIRCADIAN RHYTHM

Circadian rhythms are shifts in physical, emotional, and actions following a daily cycle. It primarily responds to light and darkness in the environment of an organism. Sleeping in the night and being up in the daytime is an example of a circadian rhythm related to light [7]. In most living organisms, including animals, plants, and many small microbes, circadian rhythms are found.

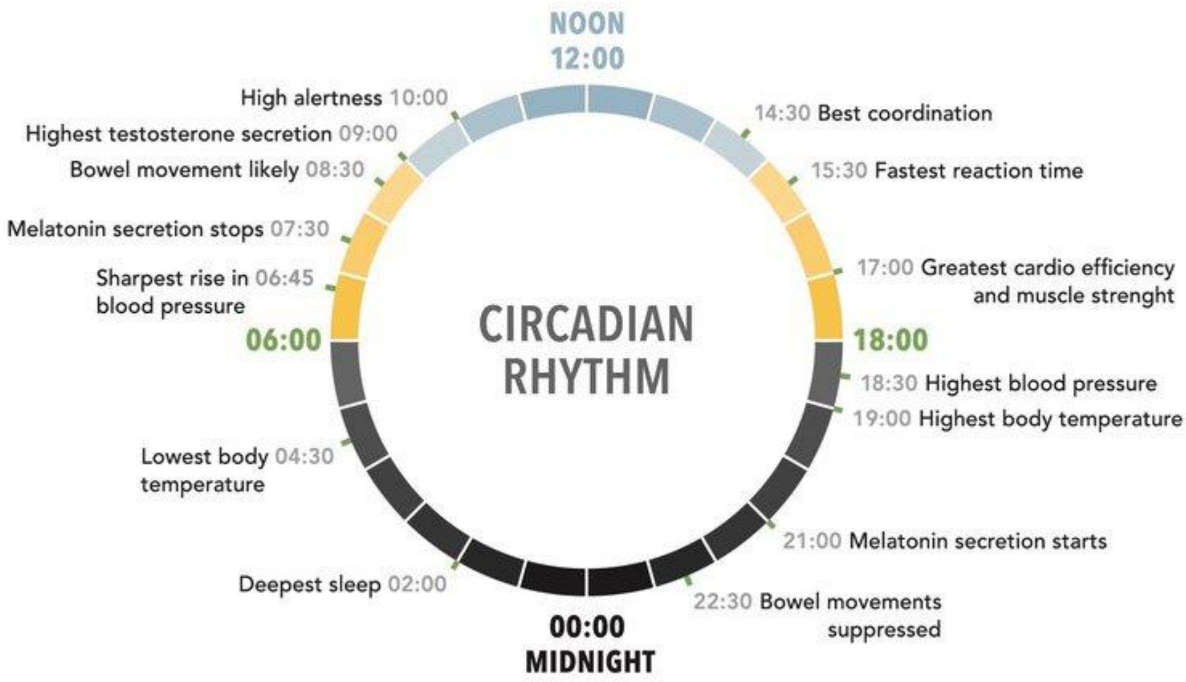


Figure 14. The natural circadian clock in human beings [6]

Melatonin and cortisol are the hormones influencing the quality of circadian rhythm. These two hormones are highly significant for the proper functioning of the human psyche. Any considerable change in the timely production over time could affect the overall health of an individual. A substantial disruption in the circadian rhythm can cause an unhealthy lifestyle leading to major diseases like insomnia and other mental health problems. The production of these two hormones for 24 hours is shown in figure 14.

The circadian rhythm in a human being is majorly affected by the lights one gets exposed to during his 24 hours routine in a day. Cortisol, which called otherwise as a stress hormone, hit the maximum production level right after we wake up in the morning. This response is described as the cortisol awakening response (CAR). In general, exposure to bright light increases the cortisol level. Naturally, the production of cortisol is aimed at the performance of the body during the high active states assisting the humans during fast reaction periods. Over the time-flow from the morning to the evening, the level of cortisol should reduce naturally, and the melatonin secretion should increase gradually.

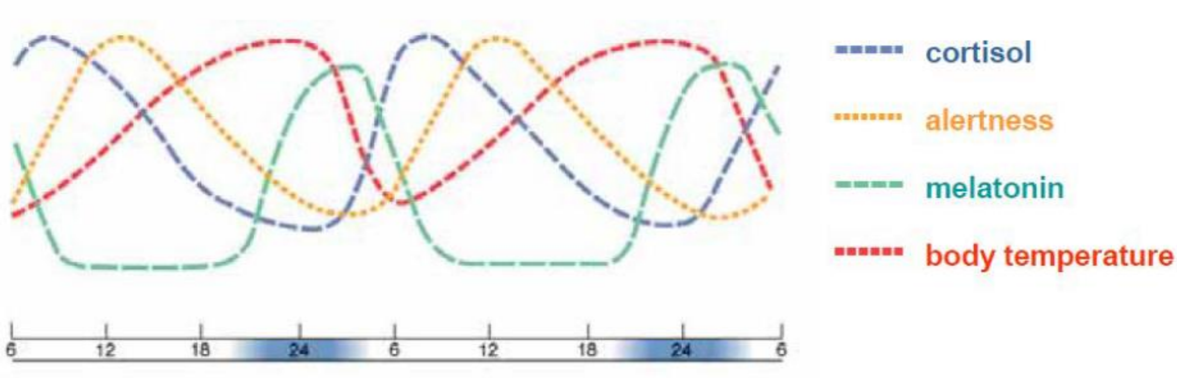


Figure 15. The production of melatonin and cortisol over a day [7]

Melatonin is a natural hormone produced in our pineal gland which regulates the sleep/wake cycle of human beings by pushing the body to a stress-free zone. According to the study [44], the exposure of an individual to lights of varying wavelengths could affect the production of melatonin. For example, exposure to bright blue light of shorter wavelength 450 nm in the evening/night could suppress the natural production of melatonin, thereby, affecting the sleep at night. Whereas, exposure to yellow-green light has shown to assist the production of melatonin.

9. ENVIRONMENTAL CONCERNS

The term "light", in our society, is having mercurial importance and the significance will keep on skyrocketing in the following future. Human beings have the authority to decide whether to implement the artificial lighting in an ecologically safe and sustainable manner. Road lighting has been the main subject of discussion when it comes to impatience or earnestness in finding a solution for tackling the environmental impacts caused by lighting. This lead to a coined term known as Light pollution. The problem of light pollution cannot be considered gently as it has the potential to become a significant, impactful phenomenon that could adversely affect our society and the ecosystem as a whole.

9.1 Light Pollution

Light pollution can be defined as pollution caused by the excess lighting leading to an inability to visualize the stars. The International Dark-Sky Association (IDA) officially defined light pollution as "any adverse effect of artificial light including sky glow, glare, light trespass, light clutter, decreased visibility at night, and energy waste". It is supposed that around 50 percent of light pollution is caused by road lighting [52]. Road lighting is a significant part of our struggle for society's safety. When properly implemented, it has the potential to provide socio-economic benefits to our world by,

- Reducing accidents
- Reducing the night-time crime rate
- Business promotion
- Efficient traffic system
- Pedestrian's safety

The more efficient use of road lighting can significantly reduce light pollution. It can be achieved by adequately utilizing and implementing suitable lighting technologies.

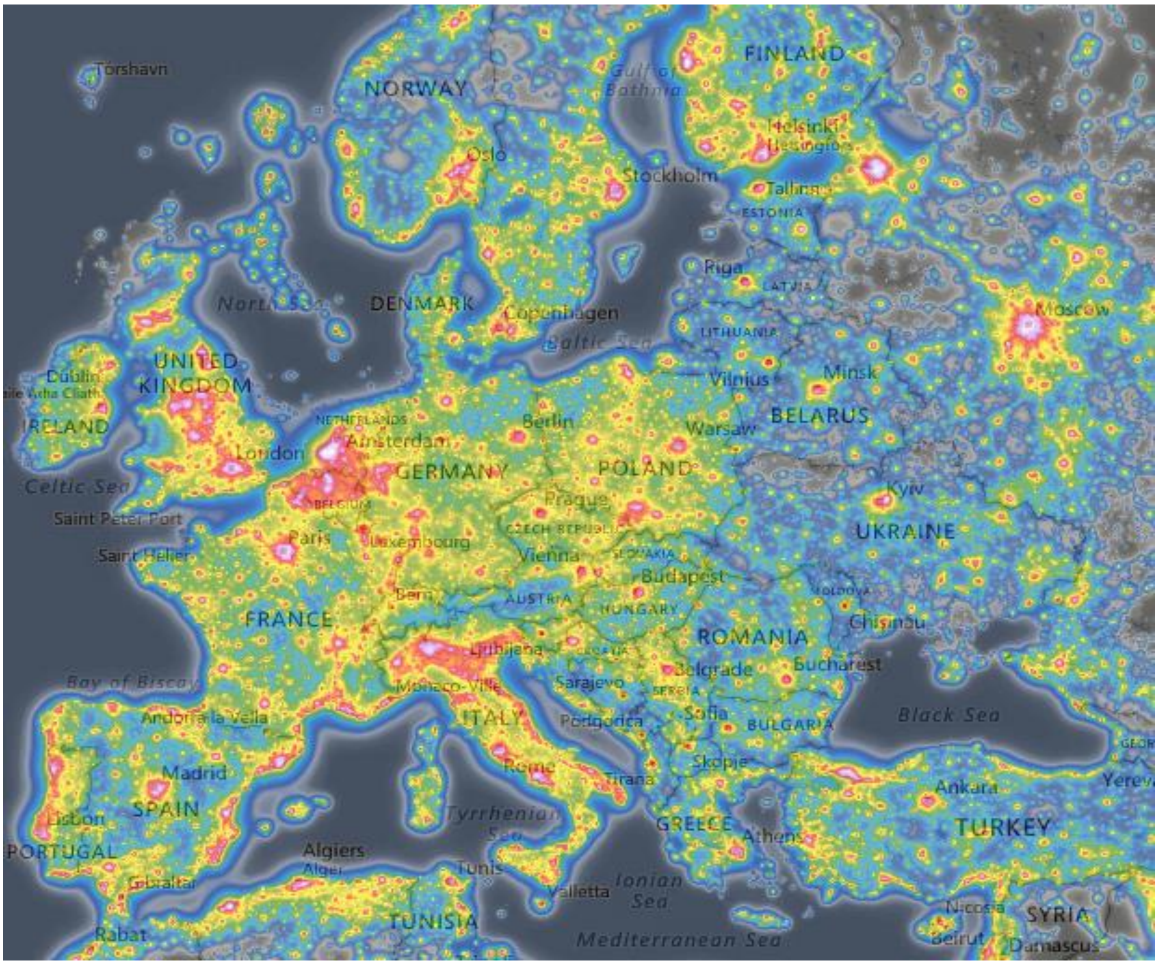


Figure 16. The light pollution across Europe in 2020 [10]

The red areas in figure 16 are the areas affected by extreme light pollution. Mostly those are the urban hubs of a country, and they have been a major, taking point for the astronomers as the light pollution obstructs their proper visibility of stars. In France, there is Paris, which is, of course, a major urban centre.

Moreover, in Germany, there is Berlin and Munich. The northern part of Italy is covered with light pollution. The Netherlands, which is considered to be the most illuminated country, is also facing extreme light pollution as of in 2020.

As light is an integral part of our society's safety and survival, it is nonsensical to obstruct the development of LED's, whose blue light is one of the main factors contributing to light pollution. Instead, as engineers and scientists, we are bound to evolve a better solution to this issue but developing the present technologies.

The light pollution is a broad term and can be classified into various types. Those being,

- Light Trespass
- Over Illumination
- Glare
- Clutter
- Skyglow

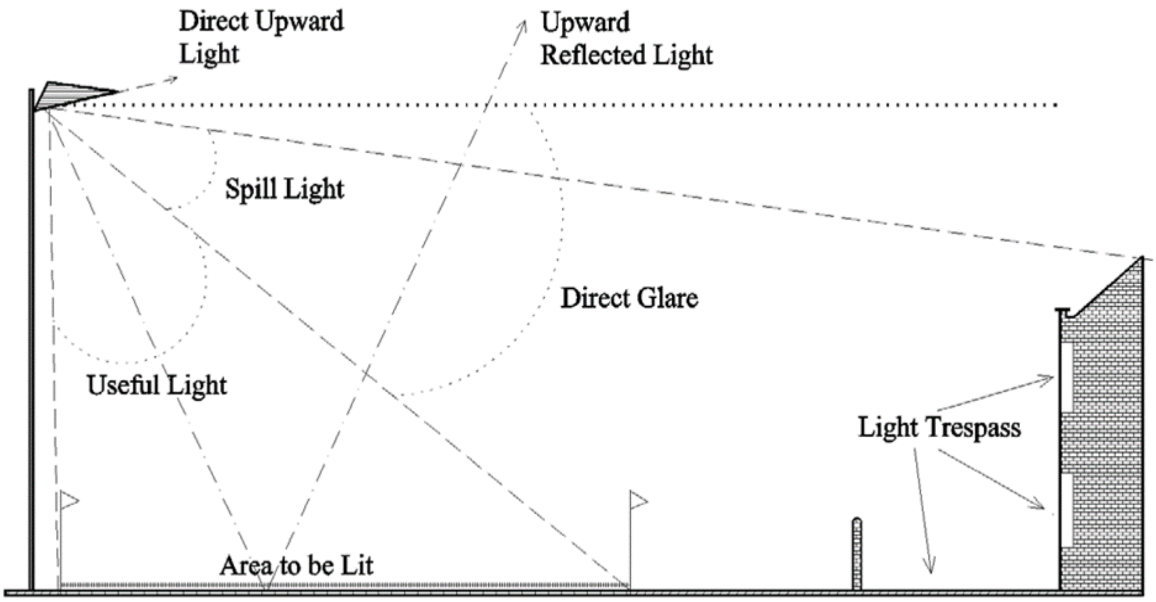


Figure 17. Different components of light pollution [11]

9.1.1. Light Trespass

The light trespass is becoming a primary concern these days because of the careless designing of the lighting system. As the name suggests, light trespassing occurs when the light unintentionally lights up some areas which are not meant to lighten up. Figure 17 shows a pictorial representation of the phenomenon. The excessive glare from the light is causing the light to trespass through the window of the house during night time, potentially affecting the sleep cycle of human beings. Moreover, this phenomenon could also lead to energy wastage. According to the International Dark-Sky Association, almost 30 percent of all the road lighting in the United States of America is lost or strayed away from the intended area [12]. The lights straying away from the intended areas are called as spill light and is considered as an energy wastage. The more uniform is the light distribution from the source, the less will be the potential energy wastage. An example of the uniformity calculation is as follows:

Light Trespass Calculation Example

The light trespass calculation is done in DIALux4 software [45], considering parameters including vertical illuminance (E_v), average horizontal illuminance (E_{havg}), and horizontal illuminance uniformity (U_{0h}). The horizontal illuminance uniformity is unitless and is measured in a scale between 0 and 1. The more uniform horizontal light distribution will have a uniformity value close to 1. For the calculation, two types of vertical illuminance are considered, the vertical illuminance at the street side where the luminaire pole (E_{v1}) is situated and the vertical illuminance at the opposite side of the street (E_{v2}).

The area taken for the calculation is the Nuselská street in Prague shown in figure 18. The luminaries are situated in the one side of the street comprising of old HPS lamps with luminous intensity distribution similar to SCHREDER MC2 PMMA SON-T 150 W Wide with a luminous flux of 17500 lm, and newly installed LED lamps. The old HPS and the new LED installation have a similar light intensity distribution. The SCHREDER 428222 AMPERA MAXI 5140 LED luminaire with a luminous flux of 16481 lm is chosen for the new installation as it satisfies the requirement of the situation [46].

Figure 18. Nuselská street in Prague with LED in the front and HPS in the back

Table 2. The calculated parameters on DIALux

Luminaire	E_{v1} (lx)	E_{v2} (lx)	E_{havg} (lx)	U_{0h}
SCHREDER MC2 PMMA SON-T 150 W Wide (HPS)	9	7.79	29	0.76
SCHREDER 428222 AMPERA MAXI 5140 (LED)	14	4.36	39	0.77
SCHREDER 428042 AMPERA MAXI 5117 (LED)	8.74	9.1	24	0.92

The result indicates that the newly installed LEDs have a negligible improvement in the U_{0h} but showing a considerable increase in the E_{v1} and E_{havg}. Another LED luminaire, SCHREDER 428042 AMPERA MAXI 5117 with a luminous flux of 14560 lm, is chosen for the purpose of optimizing the U_{0h} and E_{v1}. The new calculation showed much-improved U_{0h} with almost similar E_{v1}, considering the values obtained from HPS.

The higher horizontal illuminance uniformity signifies better luminous intensity distribution reducing the amount of spill light and, in turn, minimizing energy wastage. The DIALux calculation report will be added as the appendix of the thesis for the reference.

9.1.2. Over Illumination

Over-Illumination is the unnecessary utilization of light. Explicitly inside the United States, over-illumination is answerable for roughly 2,000,000 barrels of oil of energy wasted in each day [13]. It is additionally noted in the US Department of Energy source that business, modern and private divisions devour more than 30 percent of all energy [13]. Energy reviews exhibit that the lighting part of private, business and mechanical uses consume around 20 to 40 percent of those land employments, variable with district and land use. In this way, lighting energy represents around 5,000,000 barrels of oil every day. Moreover, the International Dark-Sky Association mentioned that around 30 percent of road lighting in the United States of America is wasted unnecessarily [12].

9.1.3. Glare

Glare is a cause of contrast between the light and dark environment in a line of vision [13]. The higher the contrast, the higher will be the glare. The glare is a significant concern while designing modern road lights. The zone of glare is shown in figure 17, and, understandably, this phenomenon is a waste of energy.

Nevertheless, glare has the potential to affect road safety adversely by obstructing the visibility of the drivers and pedestrians, partially blinding them. Glare is classified into two types, the disability glare and the discomfort glare. The disability glare reduces the contrast sensitivity of the eye as a result of the scattering of light, whereas the effect of discomfort glare depends on the individual.

LED light sources can produce a considerable amount of glare, if not used efficiently, because of their capability to produce light of high luminance. The production of glare from the LEDs are based on two circumstances [14]:

➢ The angle between the line of sight of the individual and the light source

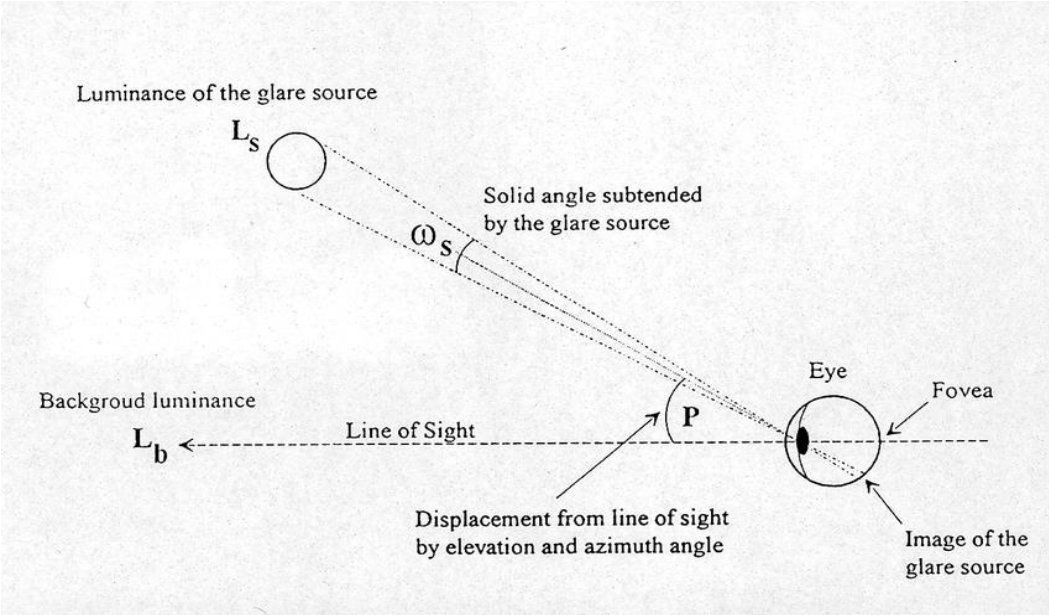


Figure 19. A simple demonstration of parameters affecting disability glare [51]

➢ The ratio between the illuminance of the light source at the eye of the observer and the background illuminance.

The Glare Rating (GR) and the Unified Glare Rating (UGR) are the terms used for measuring the glare, with the GR used in the glare calculation of outdoor lighting system and the UGR measuring the glare caused by the indoor lights [37].

According to the European Standard EN 12464-1, UGR and GR are equated as follows [37],

Unified Glare Rating,

$$\mathrm{UGR} = 8 * \log_{10}\left(\frac{0.25}{L_u}\sum_i \frac{L_i^2 * \omega_i}{P_i^2}\right)$$

➢ L_i– The luminance of the glare source 'i' in the direction of the observer's sight (cd/m²)

➢ L_u– Average background luminance (cd/m²)

➢ ω_i– The solid angle from the glare source '*i*' seen from the eye of the observer (sr)

- P_i – The position index of the glare source 'i' (Guth's index)

Glare Rating,

$$\mathrm{GR} = 27 + 24 * \log_{10}\left(\frac{L_{vl}}{L_{ve}^{0.9}}\right)$$

- L_{vl}- veil luminance of the lighting system (cd/m^2)
- L_{ve}- veil luminance of the environment (cd/m^2)

Table 3. GR Scale (DE BOER SCALE) [37]

Subjective evaluation of glare	GR index
Unbearable	90
	80
Disturbing	70
	60
	55
Just admissible	50
	40
Noticeable	30
	20
Unnoticeable	10

The disability glare is expressed in terms of threshold increment (TI). The AS/NZS 4282:2019 defines TI as "the measurement of disability glare expressed as the percentage of increase in contrast required between the object and the surrounding background for it t be seen equally well with a source of glare present".

$$\mathrm{TI} = 65 * \frac{L_v}{(L_{ad})^{0.8}}$$

where L_v – veiling luminance (lx), which is the luminance superimposed over the eye's retinal image that is produced by stray light within the eye.

L_{ad} – adaptive luminance (lx), which is the average luminance of the objects and surfaces from the observer's perspective estimating the visual range.

According to the EN13201-2 and VEJ, the glare classes for the disability glare are expressed as [14],

Table 4. Disability glare classes [14]

Shield Class	Maximum Luminous Intensity (cd/klm)			Total Shielding
	70˚	80˚	90˚	
G1		200	50	No requirement
G2		150	30	No requirement
G3		100	20	No requirement
G4	500	100	10	above 95˚ to be zero
G5	350	100	10	above 95˚ to be zero
G6	350	100	0	above 90˚ to be zero
*klm - kilolumen				

9.1.4. Clutter

Clutter is a term used in light pollution signifying the pollution caused by poorly designed needless group lighting leading to the creation of excessive glares. These glares could create confusion and strain on pedestrians and drivers, which may end up in accidents.

9.1.5. Skyglow

At Nighttime, the environment we live is getting brighter with each passing day, and it is not because of nature's abnormality, but due to the unintelligent application of available lighting technologies by humankind. We call the sky brightening phenomenon as skyglow, and it has been a significant issue in our society for a reasonable period. In 1994, as a result of a massive blackout, the people got petrified when they saw some strange cloud in the sky, and they called the authorities to inform the abnormality. As it turned out, the abnormality they witnessed in the sky is, in fact, the milky way, which has been obscured by the ever-increasing city lights [16].

The obscurity of the celestial objects caused by the skyglow is a troublesome subject for the astronomers. In order to view a star or any object in the sky distinctly, the object should have adequate contrast from the background. The visibility of the objects in the sky is inversely proportional to the magnitude of sky brightness [15].

Researcher's finding describes the effect of sky glow or generally, light pollution on human beings, plants and wildlife [17][22][32]. It adversely affects their natural livelihood and systematic pattern of survival. The following explains the light pollution's effect specifically.

9.2. Effect of light pollution on Human Beings

The research on the phenomenon called light pollution is far from conclusion, and its effect of human beings are not ideal in this era. There are many studies which suggest that prolonged exposure to lights of shorter wavelength could negatively affect our sleep pattern and could lead to a variety of diseases. The abundant exposure to artificial light caused by the light pollution emulates daylight (sun's brightness) which could negatively affect the melatonin secretion in humans leading to the disruption of natural circadian rhythm [17].

Overexposure to light pollution could cause health issues like obesity (as a result of lack of sleep) and to an extreme extend, even cancer as the suppression of melatonin secretion can promote cancer cell growth [18]. Prostate cancer is also prominent in the population with the most exposure to light pollution at night when compared with the population with the least exposure [19].

The disturbance caused by the conventional blue light from LEDs on the circadian rhythm is evident from the recent studies [17][18]. It disrupts the sleep cycle drastically leading of diseases. Light trespassing, as explained earlier, is a significant phenomenon affecting the human psyche, caused by the excessive glare from the road lights.

Figure 20. An extreme case of light trespassing [40]

9.3. Effect of light pollution on animals

The sustenance and protection of animals influence the stability of foodchain by a large margin. The moonlight is the brightest during the full moon and the dimmest on the new moon. Many species of animals, mainly nocturnal animals, depends massively on this cycle to carry out their activities. The excess artificial light produced by the road lighting system convolutes their movement patterns of such nocturnal animals and birds affecting their natural habitat [20].

The nocturnal migratory birds are more susceptible to get hurt due to light pollution. A scientific report published in the United States in the year 2018 [21] states that the migratory birds, that are naturally supposed to fly towards the horizon, get deceived by the skyglow while passing above the urban areas tricking them into flying towards the area of excessive artificial light at night (ALAN). They circle them for hours if not days and mortality rate caused by the collision of birds with the brightly lit buildings are also a point of concern. Experts say that it is possible for a human being to perceive the skyglow of an urban area from around 320 km away. For birds, the distance could be much more [21].

Figure 21. Cory’s shearwater bird grounded by bright light

According to JRC science for policy report, there are three types of effect faced by the insects when they get exposed to light pollution. They are the :

- Fixated effect – this effect draws the insects towards the light, making them stunned that they avoid feeding or evade the approaching predators.
- The crash barrier effect – this effect on the insects is caused by the clutters or excessive group of road lighting, which blocks their movement restricting them from approaching possible food sources.
- Vacuum cleaner effect – ALAN makes an area (around a distance of 60m to 600m) devoid of insects.

The sea turtle hatchlings get misguided by the skyglow caused by the ALAN on trying to find their way back to the sea. The moonlight’s reflection on the sea is the primary factor that attracts turtle hatchling towards them, but the route-finding could be difficult on a night with less moonlight.

Table 5. Effect of spectral colours on different species [22]

	UV	Violet	Blue	Green	Yellow	Orange	Red	IV
Wavelength (nm)	<400	400-420	420-500	500-575	575-585	585-605	605-700	>700
Freshwater fish	x	x	x	x	x	x	x	
Marine fish	x	x	x	x				
Shellfish (Zooplankton)	x	(x)	(x)					
Amphibia & Reptiles	x	x	x	>550	x	x	x	x
Birds	x	x	x	x		x	x	x
Mammals (excluding bats)	x	x	x	x				
Bats	x	x	x	x				
Insects	x	x	x	x				
	x - adverse effect, (x) - It is a possibility but not discerned in literature							

The above chart indicates that the spectrum of UV, Violet, Blue and to an extend, green cause more problem to the animal's vision, restricting their movement and leading to unforeseen accidents.

9.4. Effect of light pollution on plants

The green plants play a vital role in maintaining the stability of our ecosystem. Just like animals, plants have a unique significance in the survivability of our food chain. In this day and age, their survivability is under question because of human's recklessness. The artificial night light pollution has been decaying their quality for a considerable period. Plants respond differently to varying wavelengths of light in the visible spectrum, mostly in case of photosynthesis, germination of seeds and flowering. The photoreceptors in the plants track the light information and respond accordingly. It is noticeable in case of the urban environment when the ALAN causes the extension in the retainment of leaves in a plant or a tree leading to early bud burst in the spring season and makes them prone to frost damage [32].

Figure 22. The light pollution causing spring to come early [33]

Some crops like soy and maize have shown untimely speedy growth when exposed to ALAN, leading to the failure in flowering [32]. A lot of other crops has shown a reduction in their yield due to their exposition to light pollution. Darkness is vital for flora to ensure foliage recovery caused by the air pollutants and ALAN could obstruct the natural cycle.

9.5. Effect of light pollution on Astronomy

The clear perception of cosmos through highly capable telescopes of this age could lead to a lot of fantastic novel discoveries. The clear pristine night sky is an utmost necessity for the astronomers to visualize stars.

Figure 23. A picture on the left shows Andromeda galaxy in a dark sky and on the right shows the same on a light-polluted sky [31]

The pictures show the extent of light pollution's effect on the astronomers. The photographers, when focusing on astrophotography, are compelled to apply multiple light pollution filters when editing in order to deal with skyglow.

10. CONTROL STRATEGIES

The implementation of strategies to reduce light pollution has been going on for a long time. The lighting technologies are taking forward steps with time and has been improving at a considerable pace. The technological advancement in the case of LEDs is a vast concept which is yet to be uncovered ultimately. The following points mention the aspects responsible for light pollution and various ways to control it.

10.1. Light Distribution

The ratio of upward light output (R_{ULO}) determines the amount of light emitted by a light source above the horizontal plane towards the sky. It is the ratio of the luminous flux emitted by a luminaire above the horizontal plane to the total luminous flux emitted by the respective source. The higher is the R_{ULO} value; higher will be the lamp's contribution to the skyglow [14]. According to the road lighting criteria mentioned in the technical report 4.0 (TR 4.0) [22], the luminaires purchased for the road lighting should have an RULO of 0 % and should be able to withstand this limit after the tilting requirements [22].

It is practical to control and develop LED luminaire based on RULO requirements as its luminaire is comprised of reflectors, lenses, optical chambers, glass covering and diffusers [22].

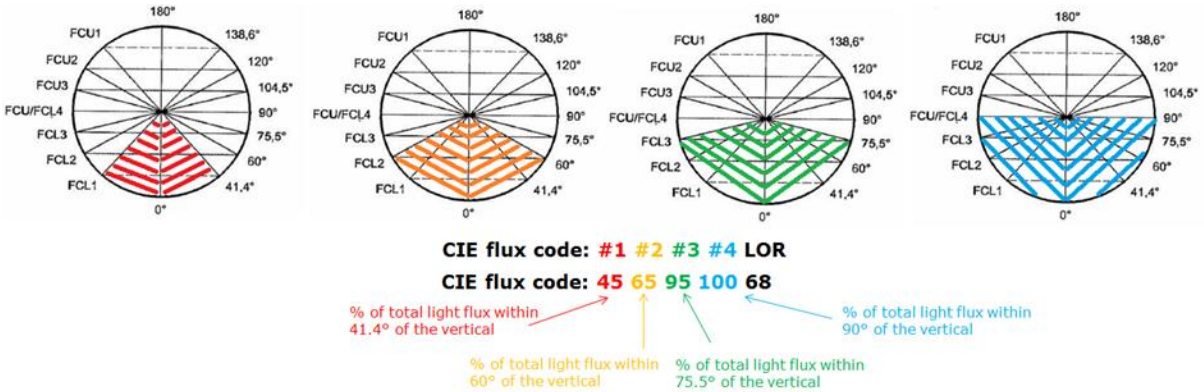


Figure 24. The CIE flux codes illustrating the light zones [22]

The LOR represents the Light output ratio which is the percentage of light leaving the luminaire out of the total light energy produced by the light source. The value of 68 indicates that, out of the total light energy emitted by the source, 68 % is leaving the luminaire. The CIE flux code stands for Commission Internationale de l'Eclairage flux code, which is a sensible representation of the luminous flux percentage emitted from a light source. The FCL 1 ≥ 45 indicates that 45 % of the LOR 68 is emitting within the vertical downward angle of 41.4 degrees whereas, FCL 4 ≥ 99 specifies that almost 100 % of the 68 % LOR emits below the horizontal plane or in other words, RULO = 0 % [22].

10.2. Lumen Output

The skyglow increases linearly with the light output [15]. The study is done by varying the output power of the light source, together with skyglow calculating its contribution to skyglow [15].

10.3. Spectral Power Distribution (SPD)

The two phenomena responsible for light pollution are the Rayleigh scattering, which is the scattering of light from the air molecules and, Mei scattering, which occurs when the light scatters from the aerosols and other atmospheric dust. Rayleigh scattering depends on the wavelength of light and is proportional to λ^{-4}, where λ is the wavelength of light [24]. Whereas, the Mei scattering is independent of the wavelength, which results in the occasional occurrence of the pale blue and white atmosphere in highly polluted areas [24]. The blue colour of the sky is the result of Rayleigh scattering as according to the phenomenon, the shorter wavelength spectral colours get scattered more than, the more extended wavelength colours [24][15]. The colour blue scatters more than the colour red when collided with the air molecules in the atmosphere. The air molecules which are abundant in the atmosphere such as nitrogen and oxygen vibrates in resonance with the lights in the ultraviolet spectrum resulting in the light to get more scattered. As shorter wavelength lights in the visible spectrum are closer to the wavelength of ultraviolet, they will scatter more than the longer wavelength lights in the visible spectrum.

The impact of light at night depends hugely on the spectral content emitted by the source. In a clear sky condition, the lights of shorter wavelength produce considerable skyglow for the near observers, whereas, the far observers experience skyglow from the longer-wavelength lights as they have the potential to travel to longer distances [15]. The sky glow will get more localized and prominent in case of clouded condition as the reflected light gets trapped by the clouds. In polluted areas with high aerosol content in the atmosphere, the difference between the skyglow caused by the shorter and longer wavelength lights over a particular distance become insignificant.

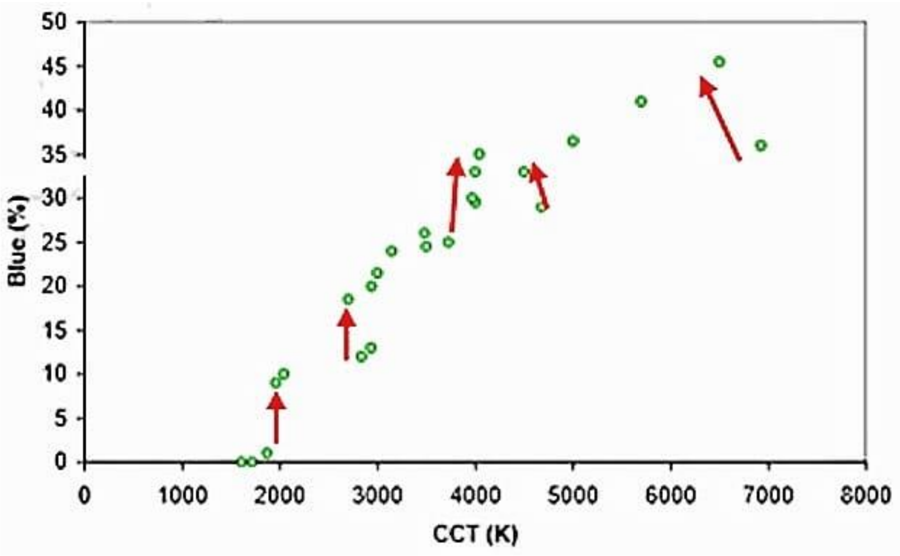


Figure 25. The percentage of blue light with respect to CCT (K) of light sources [22]

The content of blue light on variation with the CCT of different light sources, in particular, LEDs have been a subject of more significant concern. The above graph indicates that the lower the CCT, lower will be the blue light content [22].

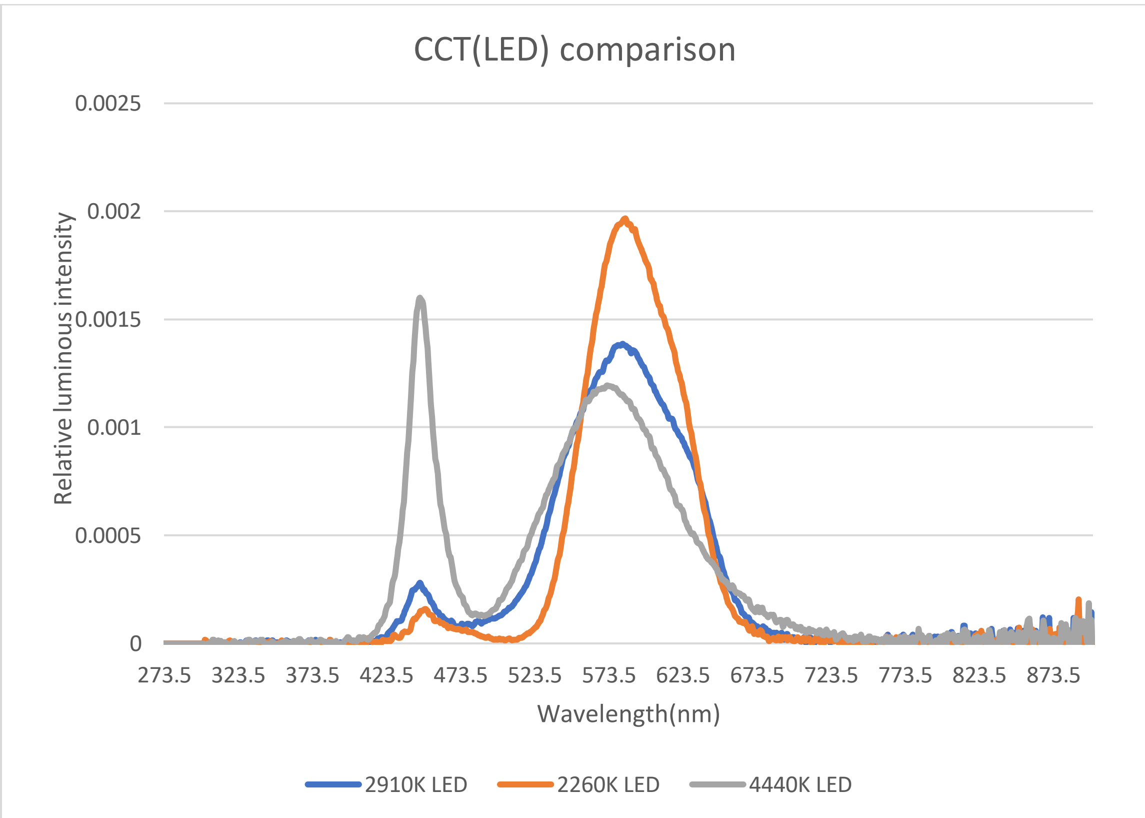


Figure 26. LEDs spectral power distribution [25]

The above graph (Figure 26) indicates the spectral power distribution of three 56 W LED road lamps of different CCTs. The LEDs used are :

- LedTech brand 2260 K 56 W
- LedTech brand 2910 K 56 W
- LedTech brand 4440 K 56 W

The spectral data of these LEDs are taken from the *LSPDD: Lamp Spectral Power Distribution Database* [25]. According to the graph, the relative intensity of blue light in LED increases with CCT value.

11. NEED FOR BLUE LIGHT QUANTIFICATION

The CCT aspect of lighting is based on the black body radiation, and the lights that emit colours closer to the black body's emission are the incandescent lamp and halogen lamp. The CCT describes the emission spectra assuming that the respective lamp behaves like a black body, which makes this phenomenon slightly unconvincing in case of lighting technologies using LED, where the colours are not close to that emitted by the black body. The concern led to the development of spectral G-index variable, which quantifies the amount of blue light content in the light source respective to the visible emission [35]. The idea was initially suggested by an astrophysicist called David Galadí Enríquez at Calar Alto Observatory.

The spectral G-index is calculated using the formula,

$$G = -2.5\ \log_{10} \frac{\sum_{\lambda=380nm}^{\lambda=500nm} E(\lambda)}{\sum_{\lambda=380nm}^{\lambda=780nm} E(\lambda).V(\lambda)}$$

- G - spectral G-index;
- λ - wavelength in nanometers;
- $E(\lambda)$ - spectral power distribution of the lamp;
- $V(\lambda)$ - luminosity function (Photopic)

The blue spectral content of a lamp decreases with increase in G-index value. The summation is calculated with a stepsize of 1 nm [35].

Advantages

- The principles are simple compared to CCT.
- Unit independent, the unit of spectral data in the y-axis are insignificant, and the calculation procedure uses the same spectrum.
- The G-index unit magnitudes are directly related to the units used in astronomy, which makes it relevant when considering skyglow.

The European Commission recommends the consideration of spectral G-index to quantify the short-wavelength content from the spectral emission of a light source in the TR 4.0 publication of Green Public Procurement of Road Lighting [22].

For the convenience in the calculation, the Andulasian representatives developed a calculation tool which will give the value of G-index after uploading the lamp spectrum. The tool is designed using Libre Office software which is free to access.

The LED road lighting lamps taken for the calculation are:

- LedTech brand 2260 K 56 W
- LedTech brand 2910 K 56 W
- LedTech brand 4440 K 56 W

The spectral power distribution of the lamps is shown in Figure 26. The respective spectral G-index values are derived after inserting the spectral values in the calculation tool.

Table 6. Spectral G-Index

Lamp	G-Index
LedTech brand 2260 K 56 W	3.2
LedTech brand 2910 K 56 W	2.36
LedTech brand 4440 K 56 W	0.74

The result reveals a convincing relationship between the G-Index and the CCT of LED lighting, with the lowest CCT 2260 K showing high G-index value and the highest CCT 4440 K revealing a low G-index. One concern is that the amount of blue light content for a particular CCT value varies with manufacturing brands. For example, the G-index value of a 2700 K LED of LedTech brands could differ from the same offered by Phillips.

The TR 4.0 strategically states that G ≥ 1.5 is entirely valid in case of CCT < 2700 K, may or may not be valid in case of CCT between 2700 K and 3000 K and totally invalid in case of CCT > 3000 K.

The European Commission considers G-index as standard that is directly linked with the blue light content and recommend its specification on the area of installation where the light pollution's effect on wildlife and astronomy is a concern [22]. The TR 4.0 recommends G-index value ≥ 1.5 for lighting installation in parks, wildlife sanctuaries and other eco-sensitive zones.

12. DYNAMIC LIGHTING

Nowadays, we all are getting accustomed to the usage of LEDs mainly because of their capability in energy savings. Over the years of research and analysis, we have to be aware of the fact that the LEDs are efficient in delivering much more than just energy conservation. The dynamic lighting is a technology developed based on the colour and luminance of LED. These lights are capable of being tuned by varying the intensity and also the correlated colour temperature (CCT).

As mentioned before, the variation in the CCT of the light determines its colour and temperature. Usually, a range between 2000 K to 7000 K is preferable in tunable white lights.

The dynamic lighting is installed in places where there is inadequate availability of natural light and is capable of duplicating the natural lighting conditions, which can influence the circadian rhythm of human beings. The variants of dynamic lighting systems are:

12.1. Dimmable

The dimmable LED system is widely used in indoors these days. It uses switches to vary the luminance and CCT. When a standard LED is dimmed, the ambience of the surroundings become bluer, as opposed to warm-dim LED, which in turn emits warmer colours when dimmed down. This system is efficient in conserving energy as they regulate the output power. In the case of road lighting, this technology is considered economically efficient and are getting popular nowadays as the traffic and lighting requirement of the road vary drastically with the weather. LEDs are efficient in dimming as they do not produce considerable colour shift when dimming as compared to metal halide and high-pressure sodium lamps [14].

Although dimmable technology has its share of advantages, when it comes to the proper regulation of circadian rhythm in human beings and technical prowess, white tunable LEDs are more advantageous than dimmable LEDs because of its capability to vary between the colours in the entire visible spectrum.

12.2. White-tunable

The white-tunable LEDs are a new class of lighting system developed mainly to stabilize the circadian rhythm of human beings. It is a recently discovered creative lighting system which can vary the colour of the LEDs by manipulating its CCT. It is to be widely considered as advantageous over dimmable design when considering the control of circadian rhythm aspect as they provide independent control over luminance and CCT. Tunable-white gives us the freedom to choose any colour of lighting based on the situation without compromising the brightness. This system is gaining popularity in indoor lighting nowadays.

13. WHITE-TUNABLE LED TECHNOLOGY FOR ROAD LIGHTING

The Digital Addressable Lighting Interface (DALI) is getting much popularity these days in case of indoors. It is an efficient lighting control system that programs the LED drivers and ballasts to work based on the condition. It is capable of delivering adequate efficiency and workability outdoors. DALI achieves the two-way communication between the lighting module and the admin interface on a computer, installed with a supervising software. Figure 27 represents the basic layout of a DALI induced white-tunable lighting system.

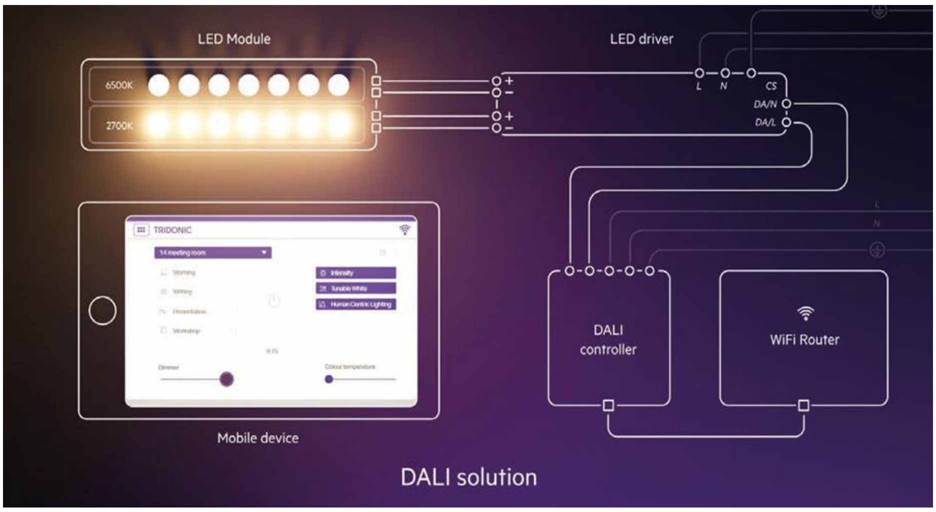


Figure 27. The basic wiring layout of an LED module with DALI [8]

The LED module shown in figure 27 has two strips of LED lights, one with a higher CCT of 6700 K and the other with a lower CCT of 2700 K. The CCT is variable between these two temperature ranges by keeping constant uniformity. The DALI provides the two-way communication between the controlling interface and the lighting system through a WiFi router.

14. CONCEPT OF BIO-DYNAMIC ROAD LIGHTING

Bio-dynamic lighting is a recently discovered idea which has been gaining popularity in the indoor lighting scenarios for the past two to three years as it can positively influence the circadian rhythm of human beings. It is a human-centric lighting system which can effectively replicate the natural daylight condition. The core of the bio-dynamic lighting system depends on white-tunable LED technology. The CCT variation in the tunable LED assists in the timely secretion of melatonin and cortisol hormones that plays a crucial role in the optimization of circadian rhythm in an individual. The lights of longer wavelength in the visible spectrum (warm lights) pose a relaxing effect to the human beings encouraging the production of melatonin hormone. In contrast, lights of shorter wavelength create an energizing impact suppressing the production of melatonin and stimulating the secretion of a stress hormone called cortisol as mentioned before in point number 7. It is backed up by a study conducted in 2018 [9], where 22 subjects got exposed to 30 minutes light pulse of varying peak wavelengths from a range of 420 nm to 550 nm during night time. It is found that considerable melatonin suppression is happening when the subjects are exposed to shorter wavelength lights (blue light). The CCT of 5000 K or above generates lights of shorter wavelengths. However, the suppression was not long-lasting as it rose back up to average around 1 hour after the beginning of the exposure [9].

The suppression of melatonin elevates the concentration of an individual keeping his/her energy level in a high state. This concept and the selective application of the bio-dynamic lighting system on a variety of roads has the potential to improve the road traffic scenario vastly. When intelligently applied, it could even reduce the adverse effect of LED lights on the Wildlife.

Kraví hora, a park in the city of Brno, witnessed an efficient installation of bio-dynamic lights in the Czech Republic, which emits a slight amber colour light after 22:00 hours at night and back to blue in the morning. A total of four lights are currently installed based on the trials conducted by the Kraví hora astronomical observatory and are planning to extend their installation covering the entire park [26]. The project aims at reducing the light pollution so that the astronomers can gaze at the night sky with clarity.

Figure 28. Bio-dynamic road light implementation in a park, Kraví hora, Brno

15. IMPACT STUDY

15.1. Influence of BioDynamic Road Lighting on Motorists

Creative implementation of bio-dynamic lights could bolster the significance of modern-day LEDs. Along with the numerous negative impacts associated with the blue spectral content of cool LEDs, there exists some positive side which can be harnessed efficiently.

The exposure to short-wavelength lights induce sleeplessness and increases the alertness by suppressing the production of melatonin hormone [28]. As explained earlier, melatonin is the sleep-inducing hormone which reduces the cognitive performance [29]. Also, prolonged exposure increases the IQ of subjects [30].

A study conducted in the year 2013 explored the impacts of CCT on the visual comfort level, alertness and task performance of students. The chosen LED CCT where 3000 K (warm white), 4000 K (cool white) and 6500 K (artificial daylight). In the result, the alertness and task performance were better when exposed to 4000 K and 6500 K lights than 3000 K [53].

When driving an automobile, one come across various type of roads, significantly differing in traffic content, people density and width. There could be some roads which are prone to animal crossing. Selective variation of CCT through the implementation of bio-dynamic lights on these roads based on the environment and time has the potential to enhance the safety of living beings. At night time, in roads which are dense with motorized traffic, the driver 's cognitive performance needs to be at the highest possible level in order to avoid any accidents. In those situations, the biodynamic lighting luminaire set with colour temperature containing an adequate amount of blue spectral content assists in maintaining the focus of the drivers. Furthermore, around midnight or after 22:00 hours, when the traffic content becomes low, the bio-dynamic lights could be programmed to reduce the colour temperature to a warmer tone (under 3000 K).

Figure 29. Sport glasses with blue and red lights [27]

A 24 Hours BMW motorsport race event took place at Nürburgring, Germany in the year 2017 witnessed a pragmatic approach to bio-dynamic lighting concept. The BMW team, along with their official partner OSRAM Licht AG, prepared the racers for the competition with blue LED light glasses to maintain their focus by stimulating their central nervous system during the strenuous 24 hour race period and, made them wear the red LED lights which helped the racers to relax during the breaks [27]. They also installed spectral luminaries in the rooms and pit wall control areas which helped the team to stay alert during the night-time session. The event was a success with no accidents.

15.2. Influence of BioDynamic Road Lighting on Pedestrians

The colour tunable aspect of biodynamic lighting system is an impactful mechanism which, upon smart and efficient implementation, could favourably influence the stability of circadian rhythm in people.

As mentioned in chapters 7 and 8, the ill-timed activation of melanopsin caused by the exposure to ALAN could disrupt one's circadian rhythm by suppressing the production of melatonin [43]. The core idea behind the biodynamic lighting system is to faithfully replicate the natural lighting condition with the utmost quality, which could significantly reduce the degree of circadian disruption.

The implementation of bio-dynamic road lighting technology in the residential areas, parks and all other pedestrian dense areas could deem highly beneficial. The smart regulation of CCT considering the density of traffic and time could reduce the adverse effect of ALAN on humans.

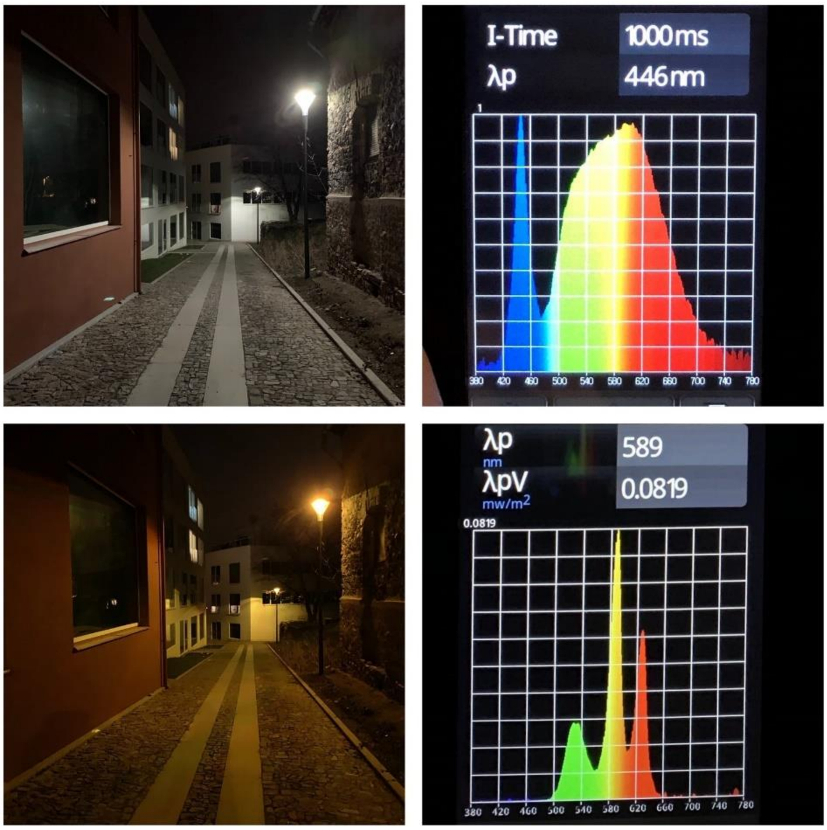


Figure 30. The variation is blue light content with CCT tuning from neutral-white(top) to amber colour(bottom), measured with a spectrometer [41]

Řevnice, a small town in the southwestern part of Prague, witnessed the first installation of the bio-dynamic lighting system in the Czech Republic. Figure 30 shows the installed bio-dynamic lighting system in the walkway connecting the residential buildings. The system provides energizing neutral white light in the evening and early morning hours and relaxing amber coloured light during the night time, favouring the circadian rhythm in people. The installation acquired a positive response from the neighbourhood [39].

15.3. Influence of BioDynamic Road Lighting on the Environment

The lights of shorter wavelength scatter more than that of longer wavelength. It is a fact and is explained sensibly in chapter 10.3. The phenomenon proves the effect of blue light on boosting skyglow. The bio-dynamic road lighting system has the provision for tuning the colour temperature as the requirement and setting an efficient schedule is entirely upon the engineers, developers and environmentalists. The usage of low CCT lighting at post evening hours could be beneficial in multitudinous ways. It helps the flora in the vicinity to maintain a stable rhythm in everyday sustenance, saving them from untimely flowering, unintended growth and unstable photosynthesis (those potential issues explained in chapter 9.4). The pollination of flowers and seed dispersal of numerous plants caused by the bats and other species of nocturnal species upon feeding on nectar and fruits at night, especially in tropical areas, are affected drastically by ALAN caused light pollution [49]. This can be rectified to an extent by implementing the biodynamic lighting technology in road lights with reduced CCT levels.

The Dutch town on Nieuwkoop experienced the installation of bat-friendly lights with a red hue, which helped ALAN sensitive species of bats and other nocturnal species in the neighbourhood to maintain their natural habitat at night. Some species of bats, namely, Myotis and Plecotus, are highly sensitive to white and green lights but are seen abundantly in areas with red ambience and darkness [48].

The preservation of the natural habitat of flora and fauna is essential for the health of the food chain. A national academy booklet on pollution states that 1/3rd of the food we are eating requires a pollinator like nocturnal insects and other diurnal species [50]. These species are sensitive to intense ALAN, causing them to stray away from their natural habitat, in turn, affecting the quality of pollination [50]. The bio-dynamic lighting could solve the issue and play a considerable role in preserving the natural habitat of organisms in the environment.

16. CLASSIFICATION OF LIGHTING AREAS

In the case of urban lighting, the two critical areas under consideration are the utility area and the architectural area. A proper road lighting system should be functionally efficient as well as visually pleasing. The lighting should satisfy the aesthetic requirement of city users without compromising the safety aspect.

16.1. Utility Lighting Areas

The design of lighting in the utility areas should be functionally active. The character of the city is expressed through its quality of illumination. These areas cover the active part of the city, which requires light during most of the night hours, from dusk to dawn.

The utility lighting areas include:

- Roads – Motorized Roads encompassing highways, ring roads, streets
- Pedestrian paths
- Cycling paths
- Riverside paths
- Squares
- Parks
- Sports areas – football stadiums, hockey stadiums, Tennis, Golf
- Commercial areas
- Industrial areas

16.2. Architectural Lighting Areas

Architectural lighting demands a lighting system which can aesthetically gratify the eye of an observer. These involve illuminating the three-dimensional buildings of either historical or administrative significance. It also involves structures like bridges, fountains, sculptures and national parks. Efficient lighting on these areas should be given utmost importance.

Generally, these areas will include:

- Historical buildings like castles, forts and palaces.
- Administrative buildings
- Artistic monuments, fountains, sculptures
- Religious buildings like churches, mosques and temples
- Cultural buildings
- Educational buildings
- Sports buildings

17. ROAD LIGHTING CLASSES

According to EN 13201, the roads are classified as M, C and P class roads considering the factors such as traffic content, separation from the carriageway, pedestrian density, cyclist roads, junction density, the speed limit, etc. [22].

- The M class roads are driveways for motorized vehicles running at high speeds. It includes highway roads having a considerable width which demands a quality level of luminance from objects, including cars and dividers, for adequate visual clarity [22].
- The C class roads will have conflicting areas where the drivers will be regularly exposed to vehicles or pedestrians and cyclists coming from other roads. The driver must be cautious while driving the vehicle as they face roundabouts, intersections, lane reduction areas, and so on [22].

- The density of pedestrians and cyclists in the P class roads are high, and the motorized vehicles move at a slower speed on pathways, residential roads, schoolyards, and so on [22].

Table 7. Light levels for each class of roads [22]

Luminance (cd/m^2)		Illuminance (lx)		Illuminance (lx)		
EN 13201	L_{max}	EN 13201	E_{max}	EN 13201	E_{max}	E_{min}
Class	cd/m^2	Class	lx	Class	lx	lx
M1	2	C0	50	P1	15	3
M2	1.5	C1	30	P2	10	2
M3	1	C2	20	P3	7.5	1.5
M4	0.75	C3	15	P4	5	1
M5	0.5	C4	10	P5	3	0.6
M6	0.3	C5	7.5	P6	2	0.4

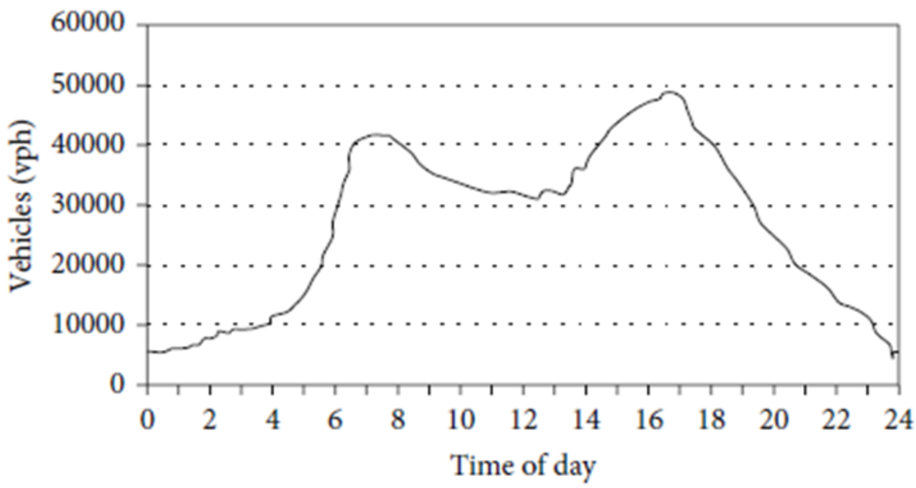


Figure 31. Traffic flow vs Time of the day [54]

18. DESIGN CRITERIA OF BIODYNAMIC LIGHTING

18.1. Efficiency criteria

According to TR 4.0 of the EU Green Public Procurement Criteria for Road Lighting and traffic signals, the luminous Efficacy drastically reduces when

CCT < 2700 K [22]. The core criteria of luminous efficacy levels from the years 2018 to 2022 are mentioned as the following:

Table 8. Luminous efficacy requirement

Year of ITT	Efficacy (lm/W)
2018-19	120
2020-21	137
2022-23	155
ITT- Invitations to tender	

In the case of dynamic lighting, the luminous efficiency varies with CCT. The luminous efficacy at CCT of 4000 K will be higher than that at 2700 K. After considering the social and economic factors, the luminous efficiency shall not go below a value of 80 lm/W at 2700 K, and they should get at least 137 lm/W at 4000 K.

18.2. Correlated Colour Temperature (CCT)

The selection of CCT for street lightings depends on the type of the road and is specific with each type. The task is extremely challenging and research are still ongoing. Usually, a range in between 3000 K to 4000 K is well advised for road lighting [14]. As biodynamic light is a form of adaptive or dynamic lighting, it is possible to tune the colour temperature back and forth, making it useful and sensible for the future road lighting applications.

In the case of M class roads, which requires a high level of cognitive performance from the drivers, it is pragmatic to implement street lights with CCT of 4000 K at least until 22:00 hours, in order to maintain the focus. The CCT of 4000 K is chosen considering the fact that it increases alertness compared to the 3000 K, and is a less potential catalyst for light pollution when compared with 5000 K lights, which has almost 3 times more blue content than 3000 K. Moreover, could reduce the temperature within the range of 2700 K to 3000 K after 22:00 hours when there will be a drastic reduction in traffic density. The time 22:00 hours is chosen taking into account a study published in the year 2014 which describes a graph about the variation in traffic density with time of the day. Figure 31 indicates that peak hour of traffic density is around 17:00 hours and the reduction in density starts from 17:00 hours until midnight and the density is considerable less from 22:00 hours to 06:00 hours in the next morning [14][24][53][54].

The C class roads will require a much higher level of awareness as it includes motorable roads, pedestrians, cyclists, intersections and roundabouts. It will be necessary to maintain a CCT range from 4000 K as it has acceptable blue light content to keep up the alertness of people and should be tuned down after 22:00 hours until 6:00 hours [24][53][54].

In P class roads, it is only necessary to maintain a CCT level within the range of 2700 K and 3000 K during the post evening hours and can be changed to a slightly higher CCT level, for example 3500 K, during early morning hours. This recommendation is justifiable as the P-type areas are filled with pedestrians, and the speed limit of motorized vehicles are considerably lower than the other two class of roads. The lower CCT produces warmer tone lights throughout the night without disrupting the circadian rhythm of the people [14][17][18][22][44][54].

The tuning of bio-dynamic lights to a lighting temperature above 4000 K and below 2700 K shall only be used under specific mandatory situation based on the requirement and shall not be used for regular road lighting purposes. This is based on considering the fact that CCT > 4000 K will emit lights of excessive blue spectral content and CCT < 2700 K is not ideal for maintaining good luminous efficiency [22].

18.3. G-Index

As the European Commission recommends the specification of G-index in case of lighting system installed in parks, wildlife sanctuaries and other ecologically sensitive areas. The biodynamic lighting shall have a spectral G-index value of ≥ 1.5 [22].

18.4. Colour Rendering Index (CRI)

The CRI determines the colour accuracy of perceived objects under lighting. It showcases precise lighting conditions. The CRI required in the M class roads shall be ≥ 70 and in C and P class roads shall be ≥ 80.

18.5. Luminous Uniformity (U_o)

The luminous uniformity shall be ≥ 0.7, which will provide adequate uniformity in the distribution of light.

18.6. Lamp Survival and Maintenance (LxBy and Cz)

As bio-dynamic lighting focuses on LEDs as the light source, the LxBy and Cz should be under consideration. Based on TR 4.0 [22], the temperature of 25˚C shall be considered as the standard for determining the rated life of LED-based luminaires. Presumably, the lifetime of bio-dynamic LEDs can be

- L96 at 6 000 hours
- C10 at 6 000 hours
- L70 at 50 000 hours (extrapolation)
- C50 at 50 000 hours (extrapolation)

The warranty period bio-dynamic LEDs road lights should be five years from the date of installation, and all those LEDs facing failure should be repaired in that period.

18.7. Luminance and Illuminance

The luminance and illuminance shall be followed based on EN13201 standard, as mentioned in table 7 of point 17.

18.8. Upward lumen output ratio (ULOR)

The ULOR should be 0 % to reduce the skyglow drastically. Moreover, they should be able to withstand the 0 % criteria even after the tilting requirements.

18.9. Glare defence

According to the shield class for disability glare mentioned in chapter 9.1.3, the biodynamic luminaire for road lighting shall have a minimum shield class of G4.

19. SAFETY CRITERIA

19.1. Ingress Protection

All the road classes shall have bio-dynamic lighting luminaires with a minimum ingress protection rating of IP65. This rating will provide efficient resistance against the ingress of dust and moisture, thereby improving the maintenance factors.

19.2. Impact Protection

All the bio-dynamic lighting luminaires shall have an IK rating of more than IK07, which will resist a minimum kinetic energy impact of 2 joules.

19.3. Over-Voltage Protection

The bio-dynamic lighting system shall be able to withstand an over-voltage level of 10 kV, considering the fact that the transient surges caused by lightning strikes could be as high as 10 kV.

19.4. Control Gear Criteria

The failure rate of control gear in bio-dynamic lighting system shall be lower than 0.2 % per 1000 hours of usage. The warranty period shall be eight years from the time of installation.

20. LABELLING OF BIO-DYNAMIC ROAD LUMINARIES

The inclusion of G-index in the TR 4.0 [22] made it possible to calculate the magnitude of blue light emission to the environment by a road lighting installation. The equation is a follows:

$$B = \frac{L}{683} * 10^{(-0.4G)}$$

- B is the blue light content (Watts)
- L is the luminous flux (lumens)
- G is the G-index (unitless)

The labelling of bio-dynamic lighting which the tenderer shall install must carry the technical specifications comprising:

- Details of the Manufacturer
- Serial number and the date of manufacture of the lighting set
- ULOR and CIE flux codes
- CCT and G-index
- Luminous flux at a temperature of 25˚C
- Power Rating
- Luminous Efficacy at a maximum CCT of 4000 K and minimum CCT of 2700 K
- Specification of bio-dynamic technology

21. FUTURE POSSIBILITIES

The TR 4.0 of the EU Green Public Procurement Criteria for Road Lighting and traffic signals [22] considers the usage of the CCT < 2700 K for road lighting as inefficient considering the luminous efficacy. As explained in chapter 6, the downconversion of blue light is the phenomenon performed in the present-day LED systems. The downconversion of blue light to lights of lower CCTs will require a considerable amount of conversion to longer wavelength colours, causing more heat loss. In an LED luminaire using a single semiconductor chip, the downconversion from blue light makes more sense than the upconversion from the red light as the frequency and energy of the shorter wavelength blue light is much higher than the longer wavelength red light. The usage of two semiconductor chips in dynamic lighting technologies could assist in improving the luminous efficiency as one chip performs the upconversion until a particular CCT, for example, until a level of around 3000 K, and the rest of the conversion can be performed through downconversion of blue light. However, this requires a proper heat sink mechanism. The idea may favour in achieving a better luminous efficacy when tuning down lights of CCT below 2700 K.

22. CONCLUSION

The technological advancement in the white tunable LED technology made it possible to consider the concept of bio-dynamic road lighting as a potential for the future. The effect of blue light on the environment has been a major talking point for last years. The countless amount of studies performed heavily emphasized on the thought of reducing the blue light content in the lighting system. This study, based on the application of biodynamic lighting concept, revolves around the idea regarding the possible area of efficient application of blue light and domain to avoid the use same.

The circadian rhythm of human beings gets disrupted upon exposure to excessive blue light, which could deteriorate the quality of life. Whereas, on the other side of the coin, the blue light shows promise in improving the alertness in an individual. Through the biodynamic road lighting, the application of the two ideas mentioned could be efficiently achieved. For example, the usage of lights of CCT above 3000 K but not more than 4000 K, with adequate blue content for road lighting in the evening and early morning hours, especially in dense traffic areas could maintain and arouse the alertness in people without destabilizing the circadian rhythm in a drastic scale. This cognitive performance arousal has the potential to reduce road accidents. Furthermore, the use of lower CCT of in-between 2700 K and 3000 K in the post evening hours on all the roads, especially in case of pedestrian rich areas like P class roads, could pose an effect similar to the natural reduction of cognitive performance, assisting people to sleep well at night.

The technical aspects related to biodynamic road lighting such as CCT, CRI, Luminance, illuminance, Lamp survival factor, safety criteria and so on, are explained in the thesis. The safe CCT range while using the biodynamic road lighting, according to the acquired data, can be considered in between 2700 K and 4000 K with respect to maintaining the energy efficiency along and the reduction of the light pollution. The spectral G-index should also be mentioned in the luminaire specification, especially installations in case of residential areas and parks, as per European commission's recommendation. The G-index measures the blue light content with respect to the visible light and its sample calculation is shown in chapter 11. The cause and the effects of light pollution on the living beings and environment are covered in the study and the control strategies comprise of the light distribution focusing on the improvement in luminance uniformity, the relation of light output with the light pollution and the fact the, the shorter wavelength lights (blue) scatters less than the longer wavelength lights (red). The R_{ULO} should be as minimum as possible and the study suggestion is to use the bio-dynamic lighting system with upward lumen output ratio (ULOR) of 0% in order to significantly reduce the light pollution as well as the energy wastage. A calculation related to light trespass is carried out in chapter 9.1.1 centralizing Nuselská street in Prague, indicating a luminaire which could emit light with more horizontal illuminance uniformity. The uniform distribution of light could lead to less energy wastage.

The guidelines for the proper handling of the biodynamic luminaire in case of road lighting is formulated considering its effect on the motorists, pedestrians and environment. These prepared guidelines are actively contemplated suggestions which could pose a positive impact on the environments and certainly, by no means unalterable. The best-case scenario could be to put these proposals in an elaborate and efficient discussion by the concerned authorities to arise with the best possible measure.

The curtailment of light pollution, albeit a small part of the huge jigsaw puzzle concerning the reduction of all environmental pollution, is a significant step-up in the right direction. The stride for its achievement is far from conclusion. The implementation of the biodynamic luminaires in road lighting could be a notable factor, having the potential to influence society in a constructive manner.

23. REFERENCES

[1] Alcon Lighting 2019, 'Colour Rendering Index – What Is CRI?', *Language of light*.
[2] Peverell, M 2019, 'What is Correlated Colour temperature (CCT)? Colour Temperature, SDCM, and Colour consistency'.
[3] Strandberg, E, & Jeff Robbins 2012, 'The Basics of LEDs'.
[4] Oseman, N 2018, 'Colour rendering index'.
[5] Lumen Learning, 'Biology II, The Senses, Vision', *Northern Virginia Community College*.
[6] Rattner, D 2019, 'How to use the psychology of light and lighting to boost your creativity'.
[7] Frackson, M, Suvagu, C 2017, 'White Tunable LED Lighting: A Literature Analysis Report Conservation and Energy Management Engineering', *BC Hydro power smart*.
[8] Tridonic 2020, 'Tunable White technology made easy Module, Driver and Controls'.
[9] Tähkämö,L, Partonen, T & Pesonen, A 2018, 'Systematic review of light exposure impact on human circadian rhythm', *Chronobiology International*, vol. 36(2), pp. 1-20.
[10] Light pollution map (2020)
URL:https://www.lightpollutionmap.info/#zoom=4&lat=5759860&lon=1619364&layers=B0FFFFFTFFFFFFFF
[11] The Institution of Lighting Engineers 2000, 'Guidance notes for the reduction of light pollution'.
[12] IDA Information Sheets, International Dark-Sky Association, Tucson, AZ URL: https://www.darksky.org/light-pollution/energy-waste/
[13] Rajkhowa, R 2014, 'Light Pollution and Impact of Light Pollution', *International Journal of Science and Research*, vol. 3, issue 10, pp. 861-867.
[14] LED Street Lighting Procurement & Design 2017, *The project funded by the European Union.*
[15] Kinzey, B, Perrin, T, Miller, N, Kocifaj, M, Aubé, M, Lamphar, H 2017, 'An Investigation of LED Street Lighting's Impact on Sky Glow', *U.S Department of Energy*.
[16] Drake, N 2019, 'Our nights are getting brighter, and earth is paying the price', *National Geographic: Starstruck*.
[17] Navara, K & Nelson, R 2007, 'The dark side of light at night: physiological, epidemiological, and ecological consequences', *Journal Of Pineal Research*, vol. 43, issue 3, pp. 215-224, 7th September.
[18] Haus, E, Smolensky, M 2012, 'Shift work and cancer risk: Potential mechanistic roles of circadian disruption, light at night, and sleep deprivation', *Sleep Medicine Reviews*, vol. 17(4), pp. 273-284.
[19] Kloog, I, Haim, A, Stevens, R & Prof. Portnov, B 2009, 'Global Co-Distribution of Light at Night (LAN) and Cancers of Prostate, Colon, and Lung in Men',

Chronobiology International, vol. 26(1), pp. 108-125.
[20] Davies, T, Bennie, J, Inger, R, Ibarra, N & Gaston, K 2013, 'Artificial light pollution: are shifting spectral signatures changing the balance of species interactions?', *Global Change Biology*, vol. 19(5).
[21] Cabrera-Cruz, S, Smolinsky, J & Buler, J 2018, 'Light pollution is greatest within migration passage areas for nocturnally-migrating birds around the world', *Scientific Reports*, vol. 8(1).
[22] Donatello, S, Quintero, R, Caldas, M, Wolf, O, Tichelen, P, Hoof, V, Geerken, T 2019, 'Revision of the EU Green Public Procurement Criteria for Road Lighting and traffic signals', *European Commission*, January.
[23] Williamson S & Cummins H 1983, 'Light and Colour in Nature and Art', *John Wiley and Sons*, Newyork.
[24] Ashdown, I 2015, 'Colour Temperature and Outdoor Lighting, Examining the Limits of CCT'
[25] LSPDD: Lamp Spectral Power Distribution Database, URL: http://galileo.graphycs.cegepsherbrooke.qc.ca/app/fr/lamps?
[26] Jablonická, K 2020, 'Stars Cannot Shine Without Darkness: New "Smart Lights" Near Brno Observatory To Help Reduce Light Pollution', *Brno daily*, 20 February.
[27] OSRAM Licht AG 2017, 'BMW motorsport'.
[28] Lockley, S , Evans, E , Scheer, F, George C. Brainard, Czeisler, C & Daniel Aeschbach 2006, 'Short-Wavelength Sensitivity for the Direct Effects of Light on Alertness, Vigilance, and the Waking Electroencephalogram in Humans', *Sleep*, vol. Sleep 29, pp. 161–168.
[29] Gubin, D, Gubin, G, Waterhouse, J, Weinert, D 2006, 'The circadian body temperature rhythm in the elderly: effect of single daily melatonin dosing', *Chronobiology International*, vol. 23(3), pp. 639–658.
[30] Lehrl, S, Gerstmeyer, K, Jacob, J, Frieling, H, Henkel, A, Meyrer, R, Wiltfang, J, Kornhuber, J & Bleich, S 2007, 'Blue light improves cognitive Performance', *J Neural Transm*, vol. 114, pp. 457-460.
[31] Celestron, Knowledgebase 2009, 'How does light pollution affect views through my telescope?'.
[32] Bennie, J 2016, 'Artificial light at night -the impact on plants and ecology', a research funded by the European Research Council, *Journal of Ecology*, pp. 611-620.
[33] Parrish, A 2016, 'Night-Time Light Pollution Causes Spring To Come Early'.
[34] P4-Your authority in self-testing emergency lighting 2017, 'IP and IK Ratings'.
[35] Junte de Andalucia 2019, 'Spectral G-Index Technical Report', *Consejería De Agricultura, Ganadería, Pesca Y Desarrollo Sostenible*.
[36] Thomas, A 2015, 'Experimental study on the effect of junction temperature on power led's', *19th International Conference on Instrumentation, Electrical and Electronics Engineering*, Warangal, August.
[37] Sawicki, D & Wolska, A 2016, 'The Unified semantic Glare scale for GR and UGR indexes', *IEEE Lighting Conference of the Visegrad Countries*

(Lumen V4), Poland, 13-16th September.
[38] Saritha, V, 2012, 'Rods and Cones', Dept. of Physiology, Amrita Institute of Medical Sciences, Kochi.
[39] Maierová, L 2018, 'Public Lighting, Public Health', VII. *Lighting Conference of the Visegrad Countries (Lumen V4)*, Prague, 18-20 September.
[40] Hecht, J 2016, 'LED Streetlights Are Giving Neighborhoods the Blues', *The Early-Adopter Blues*.
[42] Medřický, H 2018, 'Bio-dynamic Light'.
[43] Alkozi, H 2019, 'Melatonin and melanopsin in the eye: friends or foes?', *Anales De La Real Academia Nacional De Farmacia,* Spain, pp. 49-59.
[44] Grubisic, M, Hölker, F, Haim, A & Bhusal, P 2019, 'Light Pollution, Circadian Photoreception, and Melatonin in Vertebrates', *Sustainability 2019*, pp. 1-51.
[45] DIALux 4, lighting design software, http://www.dial.de
[46] Balsky, M & Terrich, T 2020, 'Light Trespass in Street LED Lighting Systems', *EPE conference 2020*, Prague.
[47] Wilm, A 2016, 'Understand the factors and adaptations that impact LED Efficiency', *LED Magazine*.
[48] Michael D'estries 2019, 'This bat-friendly town turned the night red'
[49] Rowse,E , Lewanzik, D, Stone, E , Harris, S & Jones, G 2015, 'Dark Matters: The Effects of Artificial Lighting on Bats'.
[50] Singhala, R , Kumara, M & Bosea, B 2018, 'Ecophysiological Responses of Artificial Night Light Pollution in Plants'
[51] Matusiak,B 1998, 'Daylighting in linear atrium buildings at high latitudes'
[52] Shaflik, C 1995, 'Light Pollution Environmental Effects Of Roadway Lighting', *CIVL 582 - Transportation Engineering Impacts*, 19th December.
[53] Shamsul, B, Sia, C, Ng, Y & Karmegan, K 2013, 'Effects of Light's Colour Temperatures on Visual Comfort Level, Task Performances, and Alertness among Students', *American Journal of Public Health Research*, vol. 1 (7), pp. 159-165.
[54] Nasir, M, Noor, R, Kalam, M & Masum, B 2014, 'Reduction of Fuel Consumption and Exhaust Pollutant Using Intelligent Transport System', *The Scientific World Journal*, vol. 2014, pp. 1-13.
[55] Leschhorn, G & Young, R 2017, 'Understand luminous and radiant intensity, and uniformity characterization', *Handbook of LED and SSL Metrology*, pp. 65-71.
[56] Energy.gov 2013,'History of the Light Bulb', 22nd November.
[57] Ashdown, I 2014, 'Thoughts on colour rendering', *Wordpress Blog*, 5th January.

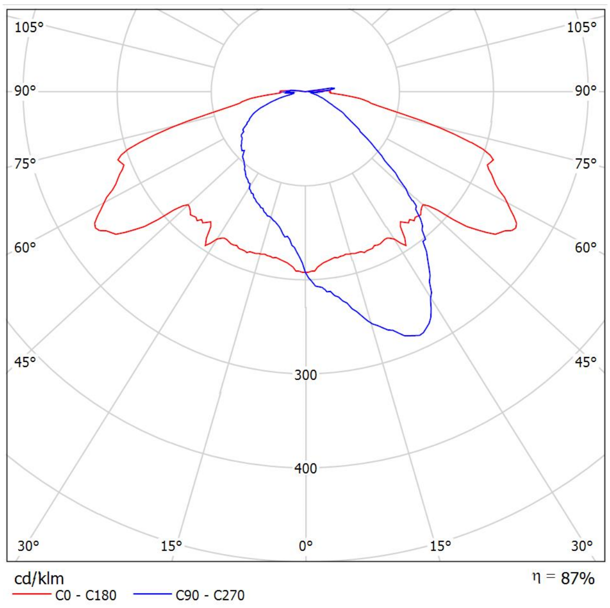
APPENDIX : Light trespass DIALux calculation example

Operator
Telephone
Fax
e-Mail

SCHREDER MC2_PMMA_SON-T_150W_Wide_861441 / Luminaire Data Sheet

Luminous emittance 1:

See our luminaire catalog for an image of the luminaire.



Luminaire classification according to CIE: 99
CIE flux code: 37 71 94 99 87

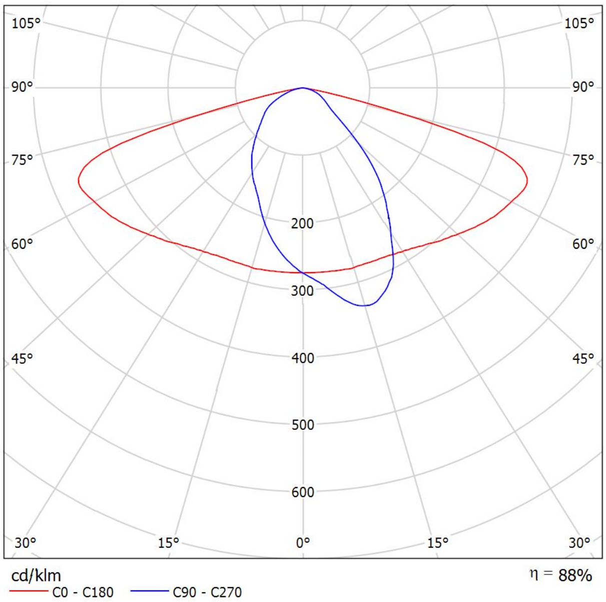
Due to missing symmetry properties, no UGR table can be displayed for this luminaire.

Operator
Telephone
Fax
e-Mail

SCHREDER 428222 AMPERA MAXI 5140 Flat glass 80 OSLON SQUARE GIANT@400mA NW 740 230V 428222 / Luminaire Data Sheet

See our luminaire catalog for an image of the luminaire.

Luminous emittance 1:



Luminaire classification according to CIE: 100
CIE flux code: 45 77 97 100 88

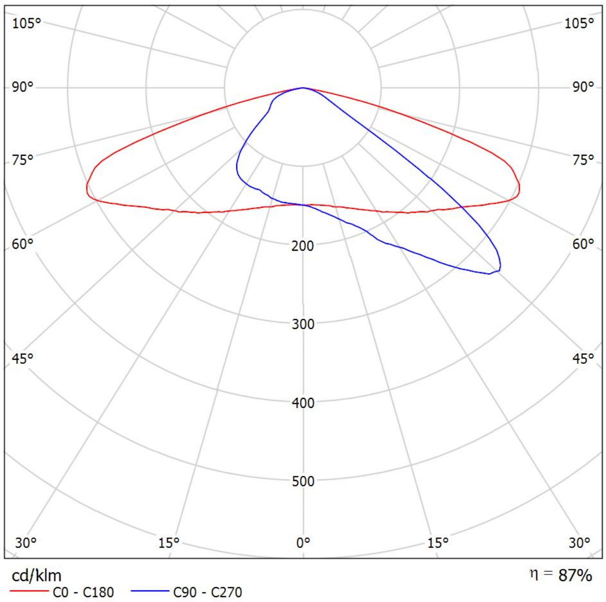
Due to missing symmetry properties, no UGR table can be displayed for this luminaire.

Operator
Telephone
Fax
e-Mail

SCHREDER 428042 AMPERA MAXI 5117 Flat glass 80 OSLON SQUARE GIANT@350mA NW 740 230V 428042 / Luminaire Data Sheet

See our luminaire catalog for an image of the luminaire.

Luminous emittance 1:



Luminaire classification according to CIE: 100
CIE flux code: 33 72 97 100 87

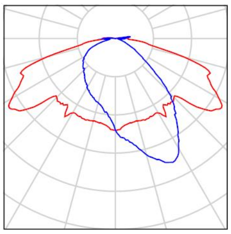
Due to missing symmetry properties, no UGR table can be displayed for this luminaire.

Operator
Telephone
Fax
e-Mail

Exterior Scene 1 / Luminaire parts list

6 Pieces SCHREDER MC2_PMMA_SON-T_150W_Wide_861441
Article No.:
Luminous flux (Luminaire): 15275 lm
Luminous flux (Lamps): 17500 lm
Luminaire Wattage: 150.0 W
Luminaire classification according to CIE: 99
CIE flux code: 37 71 94 99 87
Fitting: 1 x SON-T (Correction Factor 1.000).

See our luminaire catalog for an image of the luminaire.



Operator
Telephone
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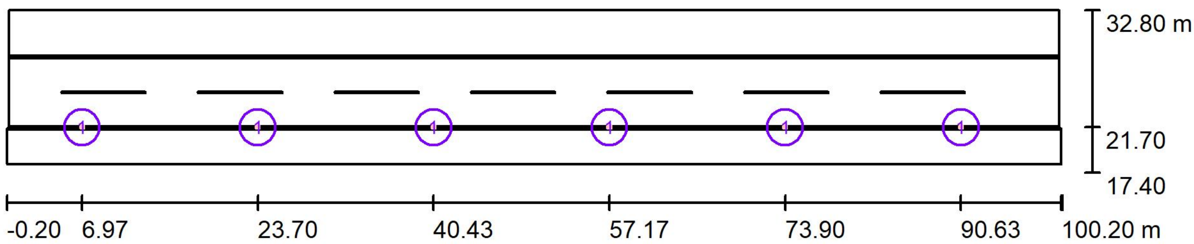
e-Mail

Exterior Scene 1 / Luminaires (layout plan)



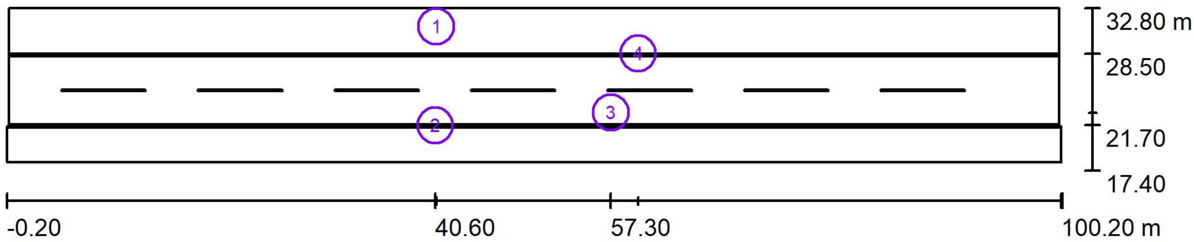
Scale 1 : 718

Luminaire Parts List

No.	Pieces	Designation
1	6	SCHREDER MC2_PMMA_SON-T_150W_Wide_861441

Operator
Telephone
Fax
e-Mail

Exterior Scene 1 / Calculation points (results overview)



Scale 1 : 718

Calculation Points List

No.	Designation	Type	Position [m] X	Y	Z	Rotation [°] X	Y	Z	Value [lx]
1	Vertical Calculation Point 2	vertical, normal	40.700	32.800	0.000	0.0	0.0	0.0	7.79
2	Vertical Calculation Point 1	vertical, normal	40.600	21.700	0.000	0.0	0.0	0.0	9.00
3	Horizontal Calculation Point 1	horizontal, normal	57.302	22.900	0.000	0.0	0.0	0.0	36
4	Horizontal Calculation Point 2	horizontal, normal	59.900	28.500	0.000	0.0	0.0	0.0	22

Summary of Results

Calculation Point Types	Quantity	Average [lx]	Min [lx]	Max [lx]	u0	E_{min} / E_{max}
Horizontal, normal	2	29	22	36	0.76	0.61
Vertical, normal	2	8.40	7.79	9.00	0.93	0.86

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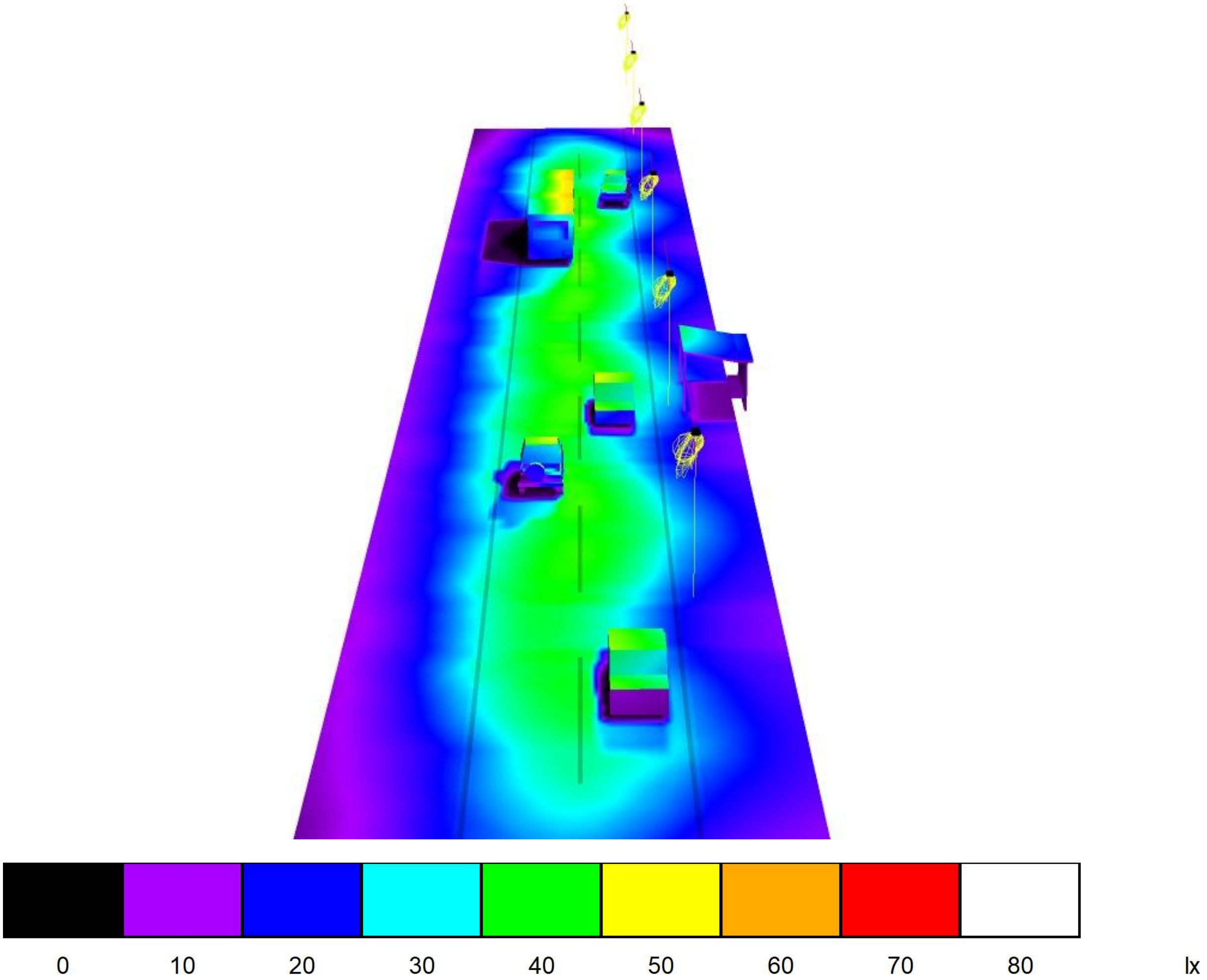
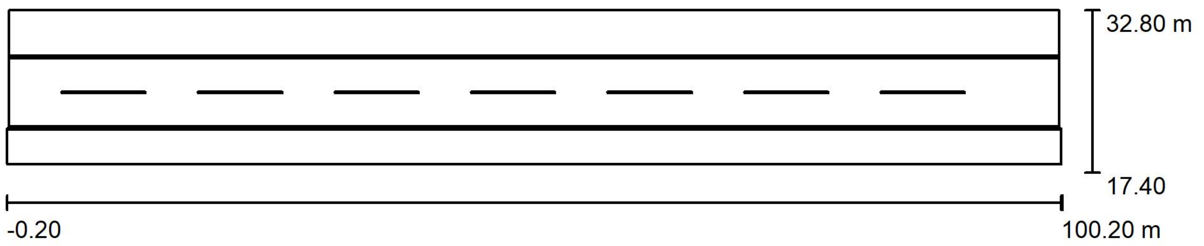
Exterior Scene 1 / False Color Rendering



Operator
Telephone
Fax
e-Mail

Exterior Scene 2 / Planning data



Light loss factor: 0.67, ULR (Upward Light Ratio): 0.0%

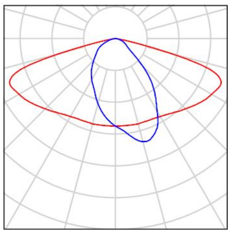
Scale 1:718

Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	6	SCHREDER 428222 AMPERA MAXI 5140 Flat glass 80 OSLON SQUARE GIANT@400mA NW 740 230V 428222 (1.000)	14448	16481	93.0
			Total: 86688	Total: 98886	558.0

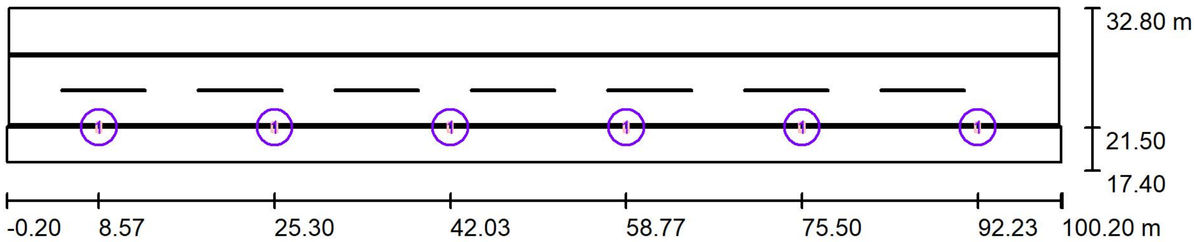
Operator
Telephone
Fax
e-Mail

Exterior Scene 2 / Luminaire parts list

6 Pieces	SCHREDER 428222 AMPERA MAXI 5140 Flat glass 80 OSLON SQUARE GIANT@400mA NW 740 230V 428222 Article No.: 428222 Luminous flux (Luminaire): 14448 lm Luminous flux (Lamps): 16481 lm Luminaire Wattage: 93.0 W Luminaire classification according to CIE: 100 CIE flux code: 45 77 97 100 88 Fitting: 1 x 80 OSLON SQUARE GIANT@400mA NW 740 230V (Correction Factor 1.000).	See our luminaire catalog for an image of the luminaire.	

Operator
Telephone
Fax
e-Mail

Exterior Scene 2 / Luminaires (layout plan)



Scale 1 : 718

Luminaire Parts List

No.	Pieces	Designation
1	6	SCHREDER 428222 AMPERA MAXI 5140 Flat glass 80 OSLON SQUARE GIANT@400mA NW 740 230V 428222

Operator
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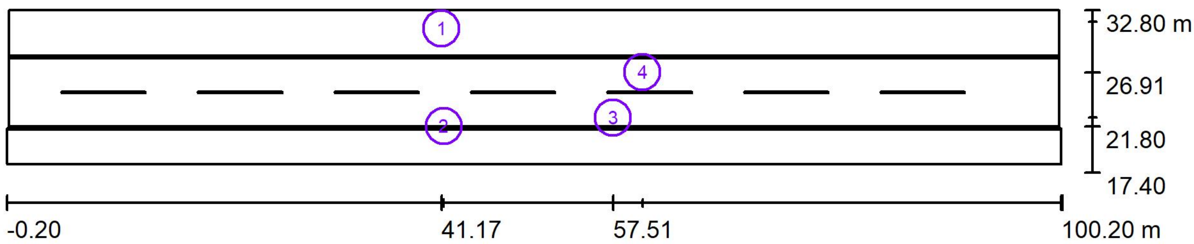
Fax
e-Mail

Exterior Scene 2 / Calculation points (results overview)



Scale 1 : 718

Calculation Points List

No.	Designation	Type	Position [m] X	Position [m] Y	Position [m] Z	Rotation [°] X	Rotation [°] Y	Rotation [°] Z	Value [lx]
1	Vertical Calculation Point 2	vertical, normal	41.172	31.731	0.000	0.0	0.0	0.0	6.17
2	Vertical Calculation Point 1	vertical, normal	41.400	21.800	0.000	0.0	0.0	0.0	14
3	Horizontal Calculation Point 1	horizontal, normal	57.509	22.600	0.000	0.0	0.0	0.0	48
4	Horizontal Calculation Point 2	horizontal, normal	60.300	26.910	0.000	0.0	0.0	0.0	30

Summary of Results

Calculation Point Types	Quantity	Average [lx]	Min [lx]	Max [lx]	u0	E_{min} / E_{max}
Horizontal, normal	2	39	30	48	0.77	0.63
Vertical, normal	2	9.86	6.17	14	0.63	0.46

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Fax
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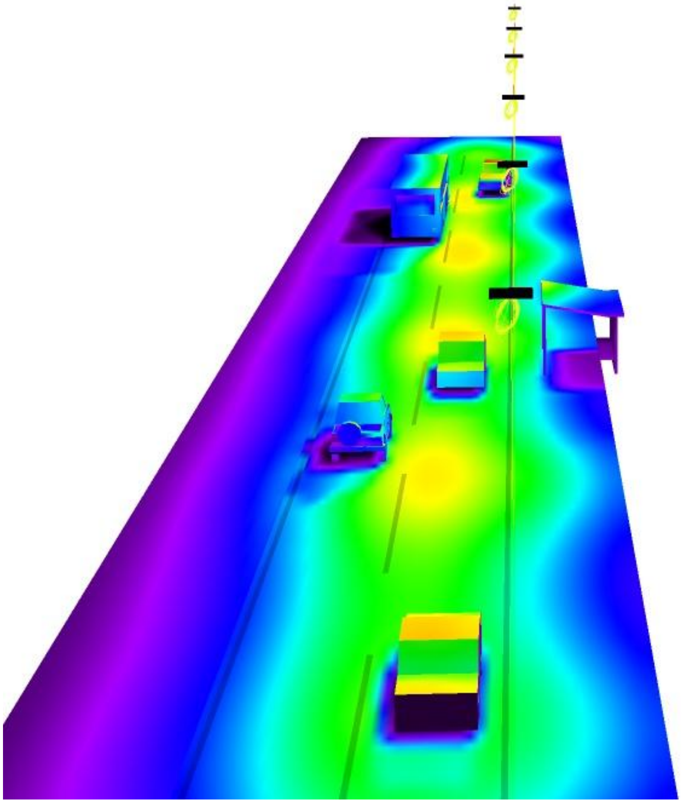
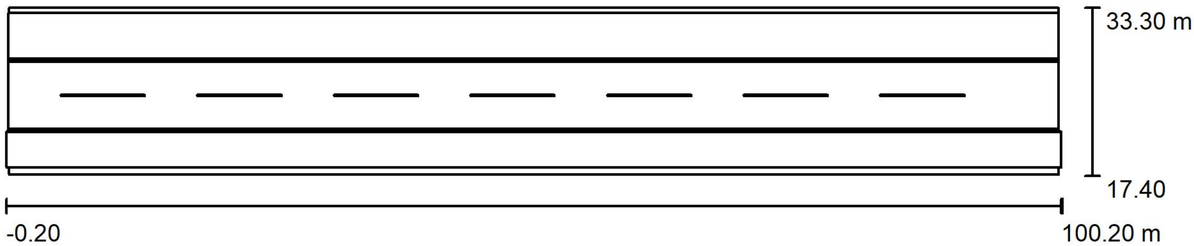
Exterior Scene 2 / False Color Rendering



0	10	20	30	40	50	60	70	80	lx

Operator
Telephone
Fax
e-Mail

Exterior 3 / Planning data



Light loss factor: 0.67, ULR (Upward Light Ratio): 0.0%

Scale 1:718

Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	6	SCHREDER 428042 AMPERA MAXI 5117 Flat glass 80 OSLON SQUARE GIANT@350mA NW 740 230V 428042 (1.000)	12682	14560	81.0
			Total: 76091	Total: 87360	486.0

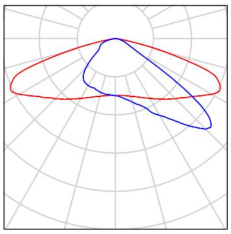
Operator
Telephone
Fax
e-Mail

Exterior 3 / Luminaire parts list

6 Pieces

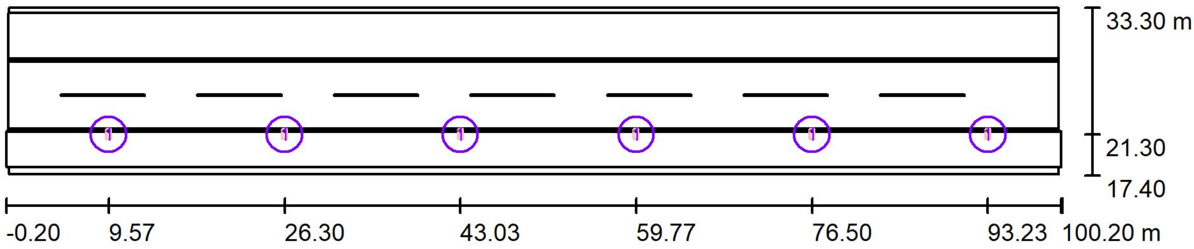
SCHREDER 428042 AMPERA MAXI 5117 Flat glass 80 OSLON SQUARE GIANT@350mA NW 740 230V 428042
Article No.: 428042
Luminous flux (Luminaire): 12682 lm
Luminous flux (Lamps): 14560 lm
Luminaire Wattage: 81.0 W
Luminaire classification according to CIE: 100
CIE flux code: 33 72 97 100 87
Fitting: 1 x 80 OSLON SQUARE GIANT@350mA NW 740 230V (Correction Factor 1.000).

See our luminaire catalog for an image of the luminaire.



Operator
Telephone
Fax
e-Mail

Exterior 3 / Luminaires (layout plan)



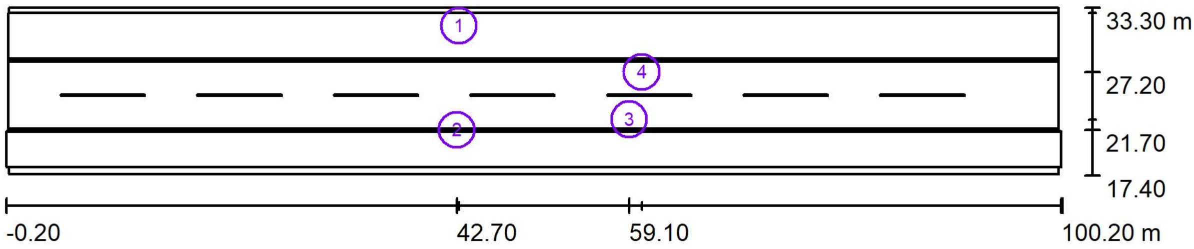
Scale 1 : 718

Luminaire Parts List

No.	Pieces	Designation
1	6	SCHREDER 428042 AMPERA MAXI 5117 Flat glass 80 OSLON SQUARE GIANT@350mA NW 740 230V 428042

Operator
Telephone
Fax
e-Mail

Exterior 3 / Calculation points (results overview)



Scale 1 : 718

Calculation Points List

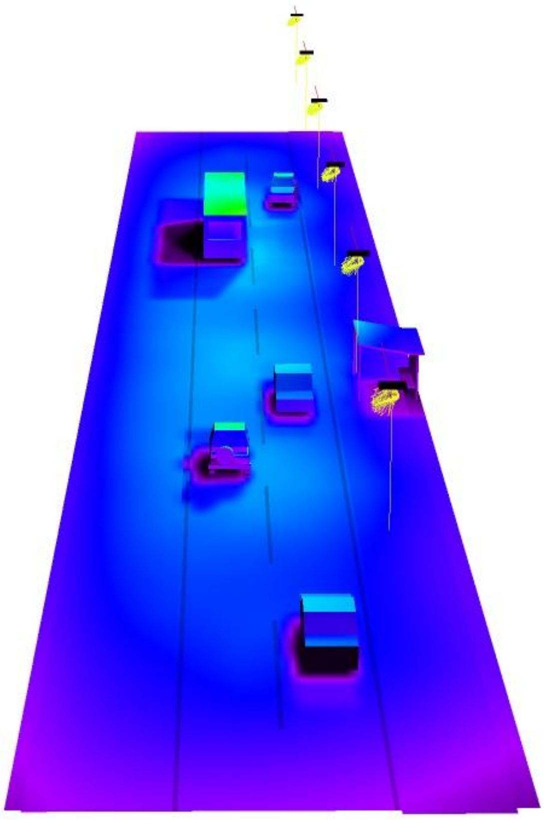
No.	Designation	Type	Position [m] X	Y	Z	Rotation [°] X	Y	Z	Value [lx]
1	Vertical Calculation Point 2	vertical, normal	42.900	32.800	0.000	0.0	0.0	0.0	9.10
2	Vertical Calculation Point 1	vertical, normal	42.700	21.700	0.000	0.0	0.0	0.0	8.74
3	Horizontal Calculation Point 1	horizontal, normal	59.100	22.700	0.000	0.0	0.0	0.0	25
4	Horizontal Calculation Point 2	horizontal, normal	60.300	27.200	0.000	0.0	0.0	0.0	22

Summary of Results

Calculation Point Types	Quantity	Average [lx]	Min [lx]	Max [lx]	u0	E_{min} / E_{max}
Horizontal, normal	2	24	22	25	0.92	0.86
Vertical, normal	2	8.92	8.74	9.10	0.98	0.96

Operator
Telephone
Fax
e-Mail

Exterior 3 / False Color Rendering



0	10	20	30	40	50	60	70	80	lx