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DEPARTMENT OF ELECTRICAL POWER ENGINEERING

Master Thesis

Advantages And Risks Of LED Luminaire For Road Lighting

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Study Programme: Electrical Engineering, Power Engineering and Management

Specialization: Electrical Power Engineering

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Czech Technical University in Prague
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DIPLOMA THESIS ASSIGNMENT

Student: **Hitesh Kataru**

Study programme: Electrical Engineering, Power Engineering and Management
Specialisation: Electrical Power Engineering

Title of Diploma Thesis: **Advantages and risks of LED luminaires for road lighting**

Guidelines:

1. Summarize requirements of european standards on road lighting systems.
2. Compare power efficiency and electrical parameters of LEDs and conventional light sources for road lighting (high pressure sodium lamps, metal-halide lamps, etc.).
3. Compare spectral parameters and effects on human eye of LED light and light of conventional sources.

Bibliography/Sources:

[1] European Standard EN 13201: Road lighting
[2] European Standard EN 62471: Photobiological safety of lamps and lamp systems
[3] DILAURA, D. A KOL. IES Lighting Handbook. 10. ed., Illuminating engineering society, 2010,1328 pages, ISBN 978-0-87995-241-9

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Prague, February 20, 2017

Declaration

I, Hitesh Kataru declare that this thesis and the work presented in it titled ‘Advantages and risks of use of LEDs for road lighting’ are my own and has been generated by me as the result of my own original research. I confirm that this work was done wholly or mainly while in candidature for Master’s degree in Power Engineering and management at Czech Technical University. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated. Where I have consulted the published work of others, this is always clearly attributed. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work. I have acknowledged all main sources of help. None of this work has been published before submission.

Date: Signature:

Acknowledgments

I would first like to thank my thesis advisor Ing. Marek Bálský, Ph.D. of the faulty of electrical engineering at Czech Technical University. The door to office Ing. Bálský was always open whenever I ran into a trouble spot or had a question about my research or writing. He consistently allowed this paper to be my own work, but steered me in the right the direction whenever he thought I needed it.

I would also like to thank Ing. Petr Zak, Ph.D. who was involved in the completion of this thesis, without his passionate participation and input, the thesis could not have been successfully completed.

Finally, I must express my very profound gratitude to my parents, brother and friends for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Abstract

The aim of this Master's thesis is to compare spectral parameters, power efficiency, electrical parameters and effects of light on human eye between LED light and conventional lighting sources. I also summarize the requirements of European standards for road lighting systems. The data was analyzed to see the effects of LED lights to humans as well as the environment and why sodium vapor lamps are widely used for road lighting systems across the world. Photometric diagrams and line spectrums were measured for different light sources to determine its light distribution, luminous flux, illuminance and color temperature.

Keywords

Traditional light sources, LED, Blue light, Flicker, Photometric diagrams, Line spectrums, light distribution, color temperature and luminous flux.

Abstrakt

Cílem této diplomové práce je porovnat energetickou efektivitu, spektrální parametry a účinky světla LED a konvenčních světelných zdrojů na lidské oko. Na základě měření spektrálních vlastností konvenčních a moderních zdrojů světla jsou v práci vyhodnoceny výhody a nevýhody LED a sodíkových výbojek pro osvětlování komunikací a jejich účinky na pozorovatele a na životní prostředí. U vybraných svítidel je vyhodnoceno prostorové rozložení svítivosti a teplota chromatičnosti. Práce též shrnuje požadavky evropských norem na osvětlovací soustavy venkovních komunikací.

Klíčová slova

Konvenční zdroje světla, LED, fotobiologické účinky světla, flicker, fotometrické diagramy, spektrum záření, teplota chromatičnosti, světelný tok.

Nomenclature

The average road surface luminance – L

The overall uniformity of the luminance - U_o

Longitudinal uniformity of the luminance – U_I

Threshold increment – TI

Surround ratio – SR

The average illuminance – E

Minimum illuminance - E_{min}

Average hemispherical illuminance - E_{hs}

Minimum semi-cylindrical illuminance – Esc,min

Minimum vertical plane illuminance – $E_{v,min}$

HPS – High pressure sodium lamp

LPS – Low pressure sodium lamp

MH – Metal halide

LED – Light emitting diode

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1. Introduction

Humans consume around 2650 billion MWh /Year of artificial light which constitutes 19% of worldwide electricity production [1]. The EU eco-design directive (2005/32/CE) insists on streamlining the energy consumption to protect environment. Following this directive incandescent lights will be phased out and Light-emitting diodes (LED) or organic light-emitting diodes (O-LED) will be used by 1.09.2016. LED's improvement of light efficacy, energy consumption and environmental advantages will bolster its use. Light-emitting diodes (LEDs) are quickly gaining popularity because of their low cost and energy consumption. In the EU, LEDs may soon overtake incandescent light sources as a preferred light source. White LEDs have different spectral characteristics which have raised some concerns about their safety: they might be harmful for human health and in particular for human eye.

2. Comparison of LED and traditional light sources

2.1. Incandescent bulbs

Incandescent bulb is a light bulb which has a wire filament heated to high temperatures that glows visible light. The filament is heated by passing an electric current and is protected from oxidation with a glass or quartz bulb which is then filled with inert gas. Incandescent bulbs have low manufacturing cost and can operate in either alternating current or direct current. However these type of bulbs are one of the least efficient, as they only convert 5% of energy into visible light and the remaining energy is converted into heat and their luminous efficacy is 16 lumens/watt. Incandescent bulbs usually have a short lifespan [7] but they have an advantage in applications, where accurate color reproduction is desired. The color rendering index of this type of bulbs is 100, which means that they are one of the best [8]. Since these bulbs use more energy than the alternatives, such as CFLs and LED lamps, many establishments and governments have restricted their application. Fig. 1 shows the Spectral power distribution of 25W incandescent light bulb with minimal amount of blue light.

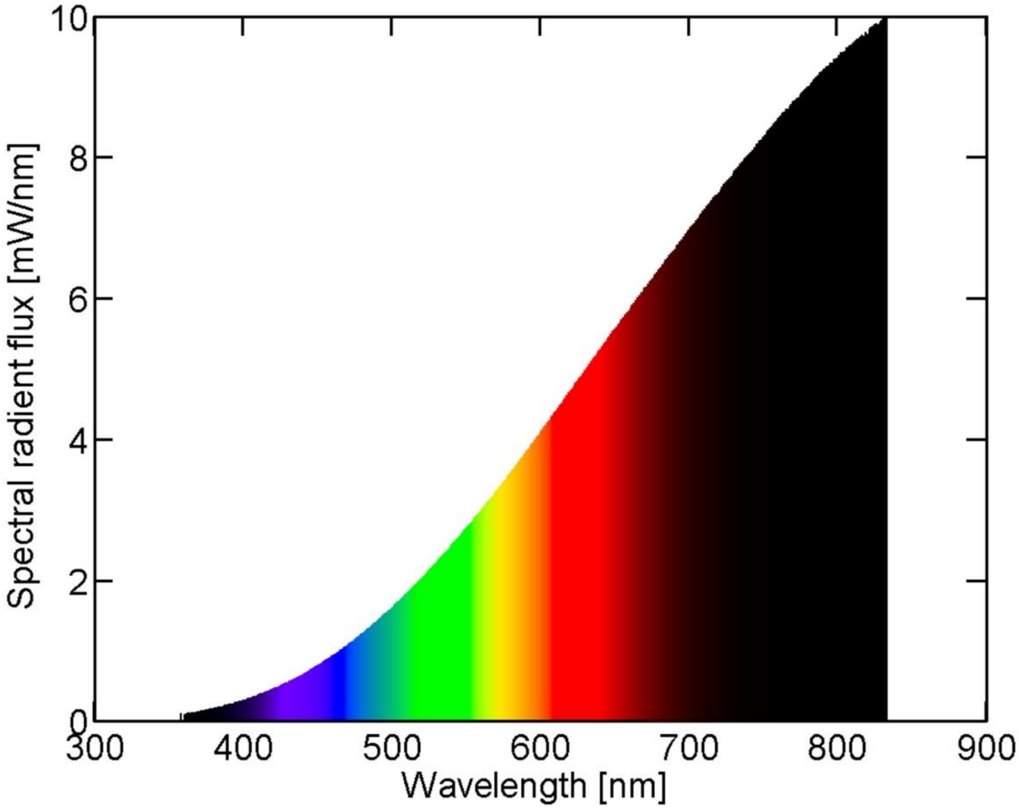

Fig. 1 Spectral power distribution of 25W incandescent light bulb [9]

2.2. Fluorescent lamp

Fluorescent lamp is a low pressure mercury vapor gas discharge that uses fluorescence to produce visible light. Electric current in the gas excites mercury vapor which produces UV light. This causes phosphor coating on the inside of the lamp to glow [10]. Fluorescent lamp is more efficient than incandescent lamp. The luminous efficacy of fluorescent lamp is 50 – 100 lumens/watt and is more expensive than incandescent lamps because of the ballast to regulate the current flowing through the lamp. The color rendering index of this type of bulbs is between 55 - 89. The use of mercury makes this type of lamp at the end of its life a hazardous waste [8].

Since fluorescent lamps are negative differential resistance devices, more current flows through them. If connected to a power supply directly, the lamp would self-destruct due to high amounts of current. In order to prevent this, a ballast is used to regulate the current flow. Various circuits can be used for operation of fluorescent lamps. The circuit is always based on AC voltage, tube length, initial cost, long term cost, instant and non-instantaneous starting etc. Fluorescent lamps can operate from a DC supply but the ballast must be resistive, which would consume as much power as the lamp [11]. Fig. 2 shows the construction of a fluorescent lamp.

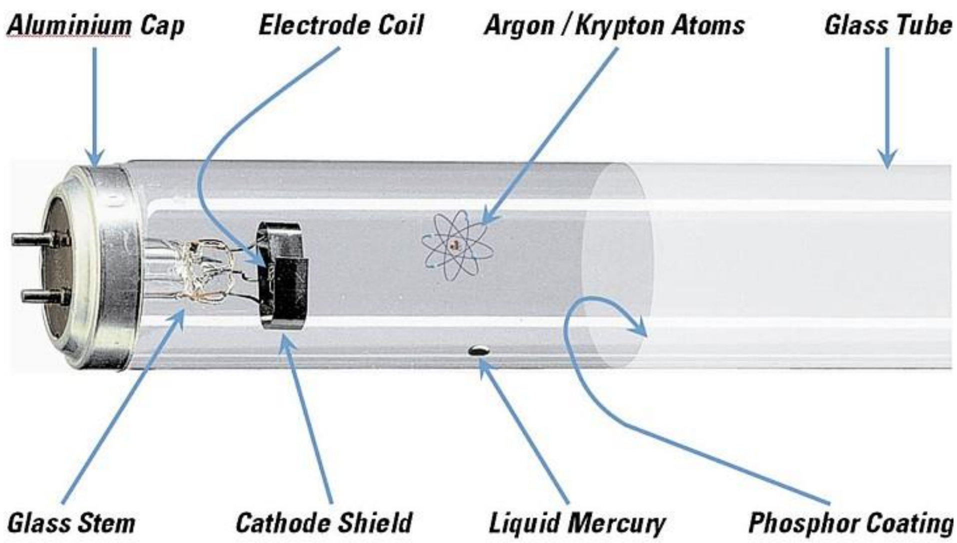

Fig. 2 Construction of a fluorescent lamp [11]

The optimum operating temperature for this type of lamp is 40°c. Only a fraction of the electrical energy is converted into visible light and the ballast dissipates some heat [13]. For every 100 incident photons of UV striking the phosphor only 86 visible light photons are emitted. [12]

2.3. Sodium Vapor Lamps

A sodium vapor lamp works on gas discharge that uses sodium in excited state to produce light. There is two types of sodium vapor lamps – low pressure and high pressure sodium lamp. The low pressure sodium lamp emits monochromatic yellow light and has color rendering index of 0, despite this it is been used for street lighting. The luminous efficacy of low pressure sodium lamp is between 100 - 200 lumens/watt. It emits light at a wavelength of 589 nm as shown in fig. 3 [24]. I have observed this in our calculations as mentioned in chapter 4.1.

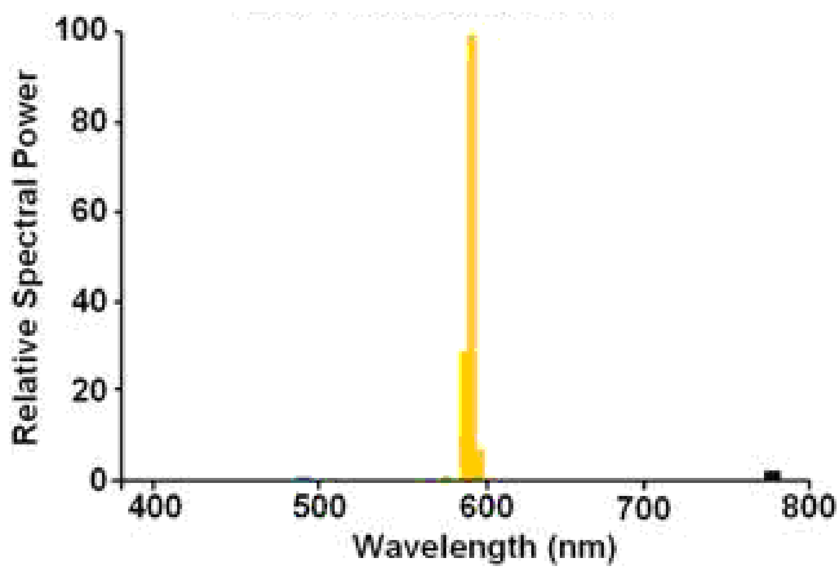

Fig. 3 Low pressure sodium lamp spectrum [29]

The high pressure sodium lamps has a color rendering index between 24 to 82. The luminous efficacy of high pressure sodium lamp is between 100 - 150 lumens/watt. It emits light at green spectrum with considerable illuminance from yellow and orange spectrums as shown in Fig. 4 [24]. I have observed in the laboratory this spectrum, which can be found in chapter 4.2.

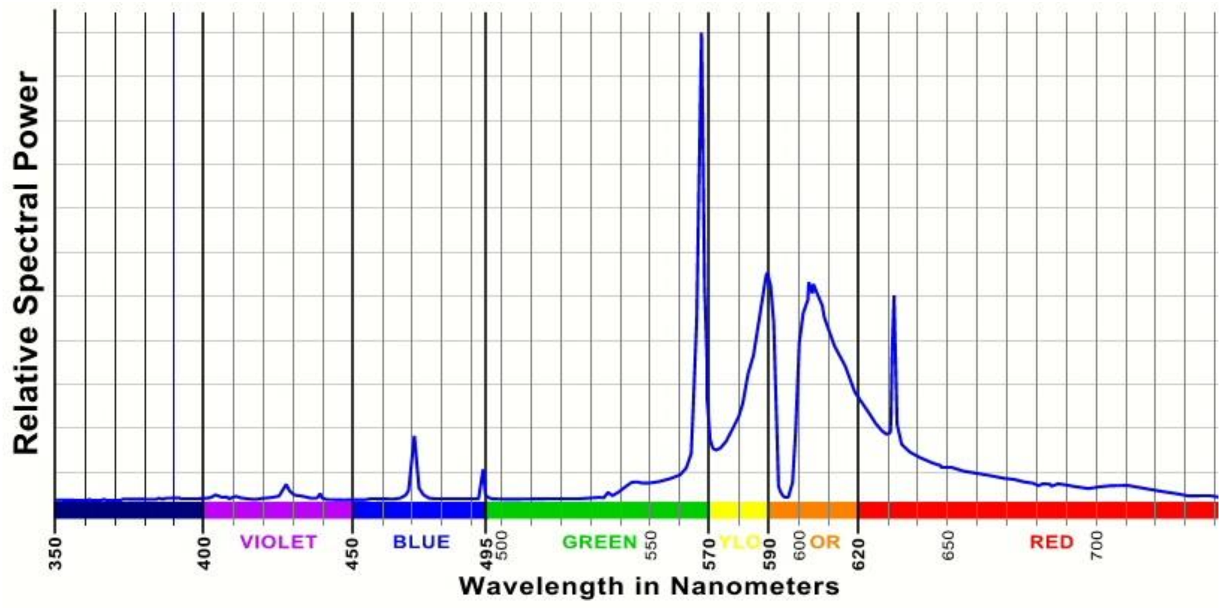

Fig. 4 High pressure sodium lamp spectrum [28]

2.4. Metal Halide Lamps

Metal halide lamp produces light by an electric arc through a mixture of vaporized mercury and metal halides. The most common metal halide compound is sodium iodide. Once the arc tube reaches its operating temperature the sodium breaks down from iodine thereby adding orange and red spectrum which is shown in fig. 5. Metal halide lamps have luminous efficacy between 75 – 100 lumens/watt. It has a color rendering index between 85 – 96 [25]. I have calculated the line spectrum of metal halide lamp which can be accessed at chapter 4.4.

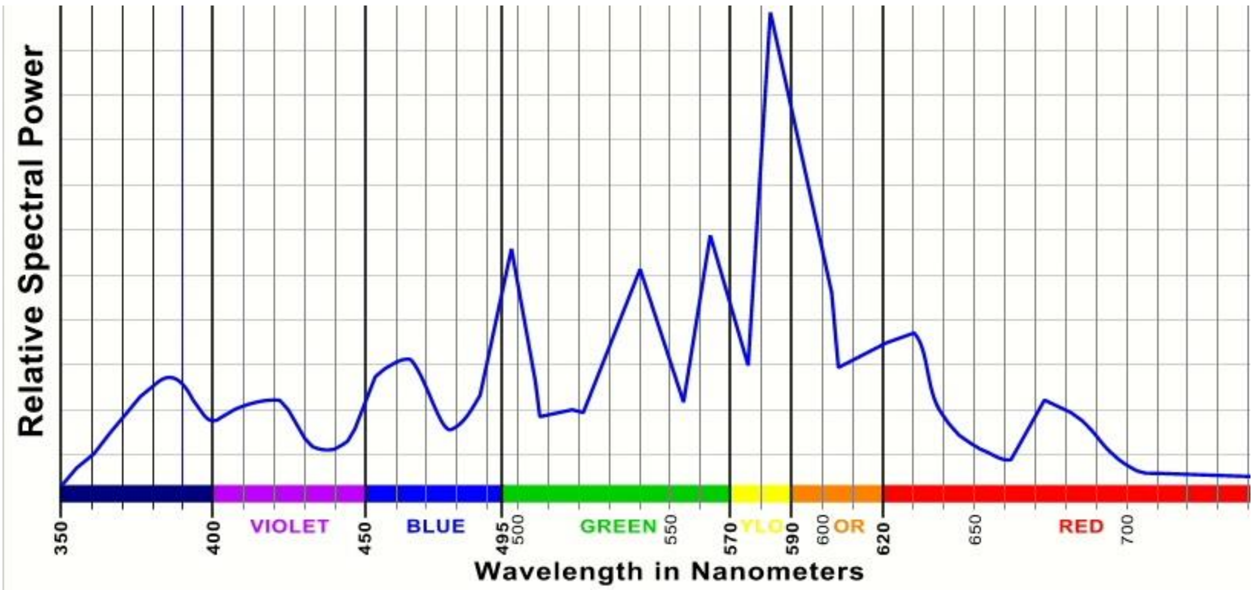

Fig. 5 Metal halide lamp spectrum [25]

2.5. LED technology

LED lighting is different from traditional lighting sources such as incandescent bulbs and compact fluorescent lamps (CFLs). They emit light in a specific direction reducing the amount of reflectors and diffusers required. This makes LEDs efficient in its lighting and cost. They also emit less amount of heat compared to the incandescent bulbs which release 90% of their energy as heat, or CFLs which release 80% of their energy as heat. [6]

LED lamps are a type of non-thermal light source as compared to incandescent light sources and halogen light sources which are thermal light sources. LEDs are dimmed by pulse width modulation which makes LEDs switch on at full intensity and then completely switch off, and then immediately switch on again. This constant on and off frequencies, which are higher than our eyes are able to discriminate, are called flicker. It is harmful to our health and overall wellbeing. Fig. 6 shows the differences in color spectrum between various light sources. From the illustrated graph we can deduce that incandescent light has the least amount of blue light compared to white LED and fluorescent lamp. [2]

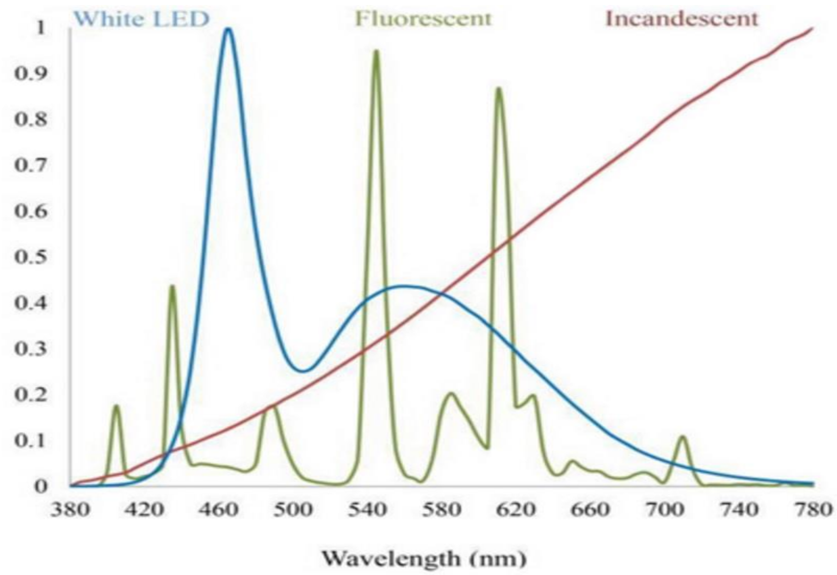

Fig. 6 Differences in color spectrum of various light sources [2]

An LED is intrinsically monochromatic, its efficiency depends on emitting wavelength. The wavelength emitted by semiconductor junction is achieved by the value of energy gap between conduction and valence bands. The major reason why LEDs are preferred is because they obtain high power efficient white LED. There are three methods of generating white light by LEDs:

- Combining a diode emitting at short wavelength λ_1 with phosphor emitting at larger wavelength λ_2 (Fig. 7)
- Using a diode emitting ultraviolent mixed with one or many phosphors
- Using three diodes emitting at different visible wavelengths which mix to produce white light [1]

The first method is commonly used for producing high luminance white LEDs. It works on the principle that two photons of complementary wavelengths reaching together on the human eye will initiate a white light sensation. Phosphor is used to cover the diode generating short wavelength, which converts them into longer wavelength photons by absorbing short wavelength photons.

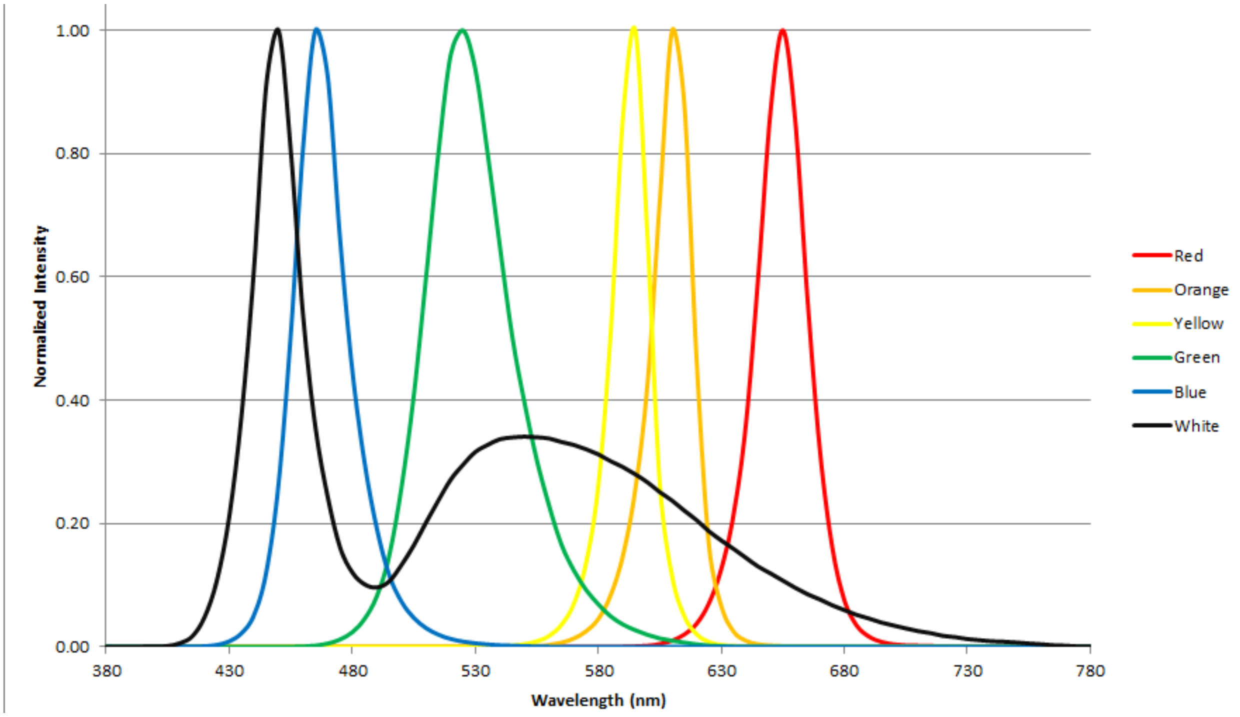

Fig. 7 Spectral graphical representation of white lights using LEDs [30]

The second method uses short wavelength diode coupled with one or more phosphors. That makes visible light by converting from UV radiation. This method has an advantage of producing high quality white light with good color rendering. This method also avoids direct emission of blue light but can cause dangerous UV emission.

The third method uses three LEDs, one for each color which is red, green and blue. The addition of these three colors produces white light. In actual use more than three sources are used to improve the color rendering. Table 1 is an example of luminance and illuminance of natural light and artificial light.

Illuminance examples (lx)	
Night sky	0,0003
75 W lamp at to 2 m	40
Public lighting	50
Very good artificial lighting	500
Outside, cloudy weather	15 000
Under the sun, during summer, at 12:00	100 000

Table 1: Examples of illuminance of natural & artificial light [1]

Compared to traditional technologies, LED technology has many benefits. LEDs are energy efficient, as they use 70% less electricity than incandescent, fluorescent and halogen options thus saving substantial energy cost. LEDs don't fail or burn out they eventually dim over time. Good quality LEDs have lifespan of 30,000 to 50,000 hours whereas traditional incandescent bulb lasts only about 1000 hours, and fluorescent lasts 8000 to 10,000 hours. This also means that LEDs reduce the maintenance cost of lighting system. Without filaments or glass enclosure, LEDs are breakage resistant and handle vibrations as well as impacts better than traditional light sources. Fluorescent and HID lamps do not provide full luminous flux upon switching on, they take time to reach their full capacity of brightness whereas LEDs have full luminous flux lighting from the moment they are switched on. [6]

2.6. LED's risks

White and blue LED have spectrums from 460 nm to 480 nm. The circadian rhythms in humans are not completely comprehended, the consequences of LED spectrum on sleep regulation remain to be researched [5]. Excess blue light from LED can induce damages to photoreceptor cells, RPE cells and ganglion cells. This blue light hazard was first discovered 40 years ago where researchers concluded that blue light causes photo chemical damages. A number of studies have shown the shorter wavelength in the visible spectrum were the most harmful to retina. It is concluded that sunlight induced retinal lesion occurring from chemical damages were similar to those after being under blue light exposure. [1]

Blue light also reduces melatonin production in your pineal gland, however cells in retina produce melatonin to regenerate it. By using LEDs we reduce the regenerative capabilities of our eye due to the presence of mainly blue wavelength and also because they have minimum red and no infrared which is necessary for repair and regeneration [4]. Fig. 8 shows the comparison between daylight, incandescent, fluorescent, halogen, cool white LED and warm white LED. We can conclude that there is a big difference between LEDs and traditional light sources. [2]

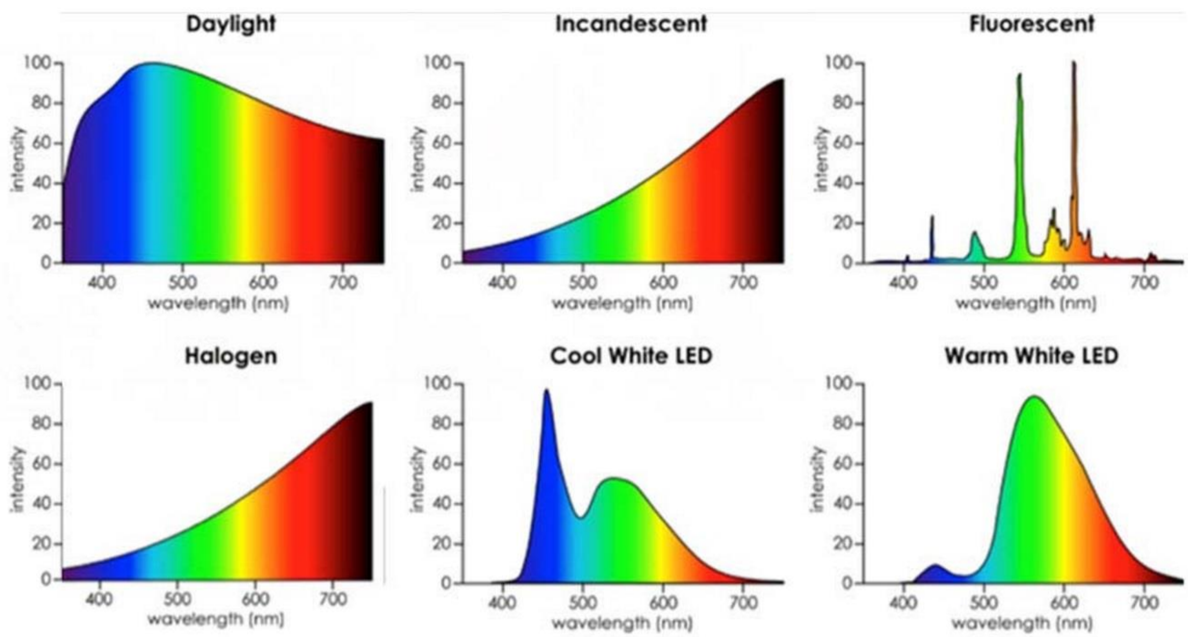

Fig. 8 Comparison between daylight, incandescent, fluorescent, halogen, cool white LED and warm white LED Spectrum [2]

There are also health risks posed by Flicker of LED lights. There is evidence suggesting that there are biological responses to flicker and health effects at higher frequencies than the visual effects of flicker [Berman and others 1991; Brundrett 1974; Colman and others 1976; Wilkins and others 1989]. The links between flicker and health have been shown to include seizures, migraines, headaches, eye strain, and reduced visual performance [Institute of Electrical and Electronics Engineers (IEEE) 2015]. [27]

At the 2016 annual meeting of the American Medical Association (AMA) a guidance for the communities was issued, which states that despite the fact that LEDs save energy when used as street lights, they create worse night time glare than conventional lighting. Blue rich LED can cause discomfort and disability which can decrease visual acuity and safety resulting in concerns and creating road hazard [3]. Recent surveys found that brighter residential night time lighting causes:

- Reduced sleep times
- Dissatisfaction with sleep quality
- Excessive sleepiness
- Impaired daytime functioning
- Obesity

AMA further explained that poorly designed LED lighting can disorient birds, insects, turtle and fish species. Many die of exhaustion, unable to break away from LED trance, some birds die from colliding with buildings lit up and others circle around the building. Recognizing the adverse effects of badly designed, high intensity LED lighting, the AMA recommends:

- To minimize and control blue rich environmental lighting by using lowest emission of blue light as possible to reduce glare
- An intensity threshold for optimal LED lighting
- All LED lighting should be shielded
- Consideration should be given to dim the LED lighting during off-peak time periods [4]

There's a strong possibility that in near future LEDs will become the main light source. Blue LEDs are usually used for decorative purposes, whereas white LEDs expose the retina to violet, indigo and blue light at higher level than traditional light sources. It will be the first time, populations are being exposed to blue light at such high levels. We might not know what are the long term risks involved with this type of exposure. There is a mandatory need for better scrutinization of potential light toxicity. [1]

Light is visible in the range of 380 – 780 nm, which is from violet to red light. The amount of energy the light carries depends on the wavelength: the shorter the wavelength, the more energy they carry. Table 2 summarizes the definition of terms.

Term	Unit	Definition
Luminous flux	Lumen lm	Evaluation according to eye sensitivity, of ligth quantity radiated in all space by a light source
Luminous intensity	Candela cd	Luminous flux emitted by solid angle unit
Luminance	Candela per square meter cd/m^2	Light surface density
Illuminance	Lux lx	Luminous flux received by a surface
Luminous efficacy	lumen/Watt lm/W	The theoretical maximum is 683 lm/W

Table 2: Definition of terms [1]

2.7. Spectral sensitivity of human eye

Photoreception in human eye occurs only in retina by three types of photoreceptor – cones, rods and intrinsically photosensitive retinal ganglion cells. The cone cells and rod cells are responsible for image forming vision whereas the ganglion cells play pivotal role in non-image forming photoreception, that is, the photoreceptive system that regulates circadian photic entrainment, pupillary light response and other important biological functions. [26]

There are three types of visions – Photopic vision, scotopic vision and mesopic vision. We will look into scotopic vision as we deal with artificial light exposure. Scotopic vision is defined as the vision of the eye under low light conditions. Since cone cells are non-functional in low light, rod cells are required to produce scotopic vision with maximal sensitivity at the wavelengths 491nm (green-blue). Scotopic vision occurs in luminance levels of 10^{-3} to 10^{-6} cd/m^2. The spectral sensitivity function of the human eye for daylight conditions is defined by CIE as illustrated in Fig. 9. By a convention, these sensitivity functions are normalized to a value of 1 in their maximum. [14]

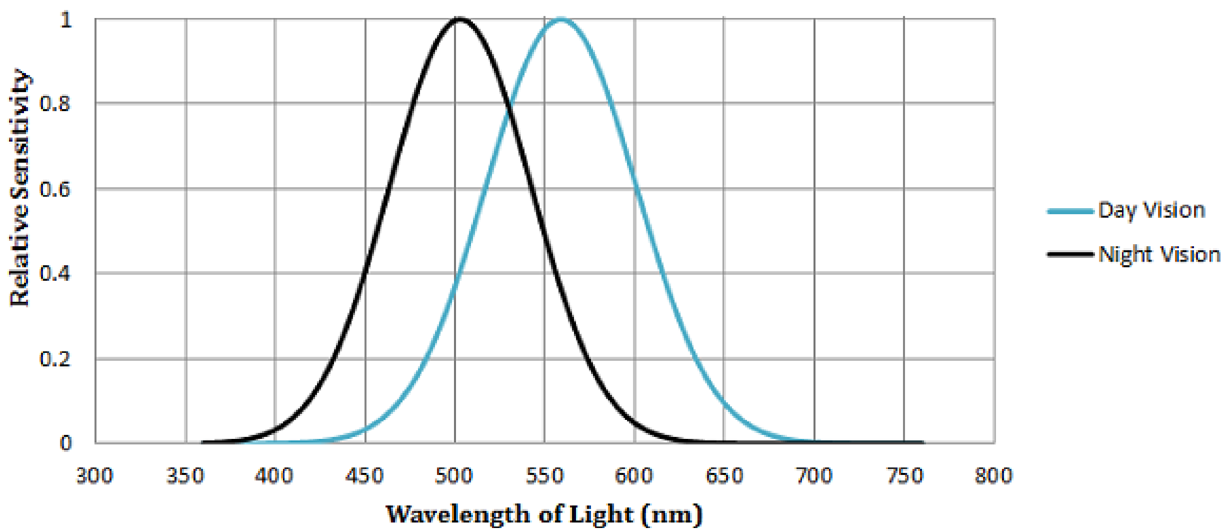

Fig. 9 Spectral sensitivity curve describing photopic vision and scotopic vision. [31]

LED lighting is becoming increasingly common in our society and it is important to consider the spectral output and flicker of the LED light source to minimize the harmful effects that is associated with blue light exposure. Since we know the adverse health effects of flicker and that there are many low cost products available with appreciable blue light spectrum, it would seem logical to prefer LEDs with wavelength around 470 – 480 nm over the LEDs which have spectral wavelength < 450nm.

3. European Standard EN 13201-2:2015 for road lighting

The purpose of this standard is to make it easier to develop and use road lighting products and services in CEN member countries. The lighting classes were defined by taking into consideration the road lighting standards in these countries and subclasses reflect particular situations and national approaches based on traditional, climatic or other conditions.

3.1. M series of lighting classes

The M class in table 3 are intended for drivers of motorized vehicles on traffic routes of medium to high driving speeds.

These are to be calculated and measured in accordance with EN 13201:2015.

Class	Luminance of the carriageway for the dry road surface condition			Disability glare TI	Lighting of surroundings
	L_{av} [cd/P2]	U_o (U_{ow})	U_l	f_{TI} [%]	EIR
M1	2,00	0.40 (0,15)	0.70	10	0,35
M2	1.50	0.40 (0,15)	0.70	10	0,35
M3	1,00	0.40 (0,15)	0.60	15	0,30
M4	0.75	0.40 (0,15)	0.60	15	0,30
M5	0.50	0.35 (0,15)	0.40	15	0,30
M6	0.30	0.35 (0,15)	0.40	20	0,30

Table 3: M series of lighting classes [23]

The average luminance (L) reflects the general luminance at which the driver performs. At the low level of lighting used for road lighting, performance improves with luminance level.

The overall uniformity (U_o) measures in general variations of luminances and indicates how well the road surfaces as background for road markings, objects and other road users.

The threshold increment (TI) indicates that although road lighting improves visual conditions it also causes disability glare to a degree depending on the type of luminaires, lamps and geometric situation.

3.2. C Series of lighting classes

They are intended for drivers of motorized vehicles and other road users on conflict areas such as shopping streets, road intersections of some complexity, roundabouts, queuing areas etc. Shown in table 4.

The average illuminance (E) and overall uniformity of the illuminance (U_0) are to be calculated and measured in accordance with EN 13201:2015.

Class	Illuminance of the carriageway for the dry road surface condition	
	E_{av} [lx]	U_o
C0	50	0.4
C1	30	0.4
C2	20	0.4
C3	15	0.4
C4	10	0.4
C5	7.5	0.4

Table 4: C series of lighting classes. [23]

3.3. P, HS, SC and EV series of lighting classes

The P and HS classes in tables 5 and 6 are intended for pedestrians and pedal cyclists on footways, cycle ways, emergency lanes and other road areas lying separately or along the carriageway of a traffic route, pedestrian streets, parking places, schoolyards etc.

SC classes in table 7 is intended as additional classes for pedestrian areas for the purpose of reducing crime and suppressing feelings of insecurity.

EV classes in table 8 is intended for additional classes in situations where vertical surfaces need to be seen.

Class	Horizontal Illuminance		Additional requirements	
	Horizontal Illuminance	Minimum horizontal illuminance	Minimum vertical illuminance	Minimum semi cylindrical illuminance
	$E_{h\ av}$ [lx]	E_{min} [lx]	$E_{v\ min}$ [lx]	$E_{sc\ min}$ [lx]
P1	15,0	3,00	5,0	5,0
P2	10,0	2,00	3,0	2,0
P3	7,50	1,50	2,5	1,5
P4	5,00	1,00	1,5	1,0
P5	3,00	0,60	1,0	0,6
P6	2,00	0,40	0,6	0,2

Table 5: P series of lighting classes [23]

Class	Hemispherical Illuminance	
	Hemispherical illuminance	Overall Uniformity
	$E_{hs\ av}$ [lx]	U_0
HS1	5,00	0,15
HS2	2,50	0,15
HS3	1,00	0,15
HS4		

Table 6: HS Series of lighting classes [23]

Class	Semicylindrical Iluminance
	$E_{sc\ min}$ [lx]
SC1	10,0
SC2	7,50
SC3	5,00
SC4	3,00
SC5	2,00
SC6	1,50
SC7	1,00
SC8	0,75
SC9	0,50

Table 7: SC series of lighting classes [23]

Class	Vertical Illuminance
	$E_{v\ min}$ [lx]
EV1	50
EV2	30
EV3	10,0
EV4	7,50
EV5	5,00
EV6	0,50

Table 8: EV series of lighting classes [23]

3.4. Appearance and environmental aspects

The design and siting of road lighting installations and equipment can make a great difference to the appearance of the road and road environment, by day and by night. This applies not only to the road user but also to the observer viewing the installation from some distance off the road.

Consideration shall be given to the following matters related to:

a) Day time appearance:

- Choice of supporting method, for example columns with or without brackets, suspension wires or direct mounting on buildings
- Design and color of lighting columns
- Scale and height of lighting columns or other suspension elements in relation to the height of adjacent buildings, trees and other salient objects in the field of the view
- Location of lighting columns in relation to views of scenic value
- Design, length and tilt of brackets on columns

- Tilt of luminaire
- Choice of luminaire

b) Night time appearance and comfort:

- Color appearance of the light
- Color rendering of the light
- Mounting height of the luminaire
- Lit appearance of the luminaire
- Lit appearance of complete installation
- Optical guidance by direct light from luminaire
- Reduction of light levels in periods

c) Minimizing light emitted in directions where it is neither necessary nor desirable:

- In rural or suburban communities, the obtrusive view of the road lighting installations seen at a distance across open country
- Light intruding into properties
- Light when emitted above the horizontal which, when scattered in the atmosphere, obscures the natural sight of the stars and impairs astronomical observation. Light emitted above the horizontal can be regulated by restriction of the upward light output ratio.

3.5. Luminous intensity classes

In some situations it can be necessary to restrict disability glare from installations where the threshold increment (TI) cannot be calculated.

Class	Maximum luminous intensity in cd / klm			Other requirements
	at 70° [a]	at 80° [a]	at 90° [a]	
G1		200	50	None
G2		150	30	None
G3		100	20	None
G4	500	100	10	Luminous intensities above 95° [a] to be zero
G5	350	100	10	Luminous intensities above 95° [a] to be zero
G6	350	100	0	Luminous intensities above 90° [a] to be zero

Table 9: Luminous intensity classes [15]

3.6. Lighting of pedestrian crossings

Pedestrian crossings can require special consideration. In some countries national standards exist which give further guidance relative to national practices.

When a sufficiently high road surface luminance level can be provided, it can be possible to position the normal road lighting luminaries so as to provide good negative contrast with the pedestrian visible as a dark silhouette against a bright background. The intention is to directly illuminate pedestrians on or at crossings and to draw the attention of drivers of motorized vehicles to the presence of crossing. [32]

3.7. Limiting obtrusive lighting

Obtrusive light is a form of light pollution which can cause physiological and ecological problems if not addressed. Sky glow, which is the brightening of the night sky, and glare, which is the uncomfortable brightness of a light source when viewed with a darker background. Figure 10 shows different ways light pollution can occur.

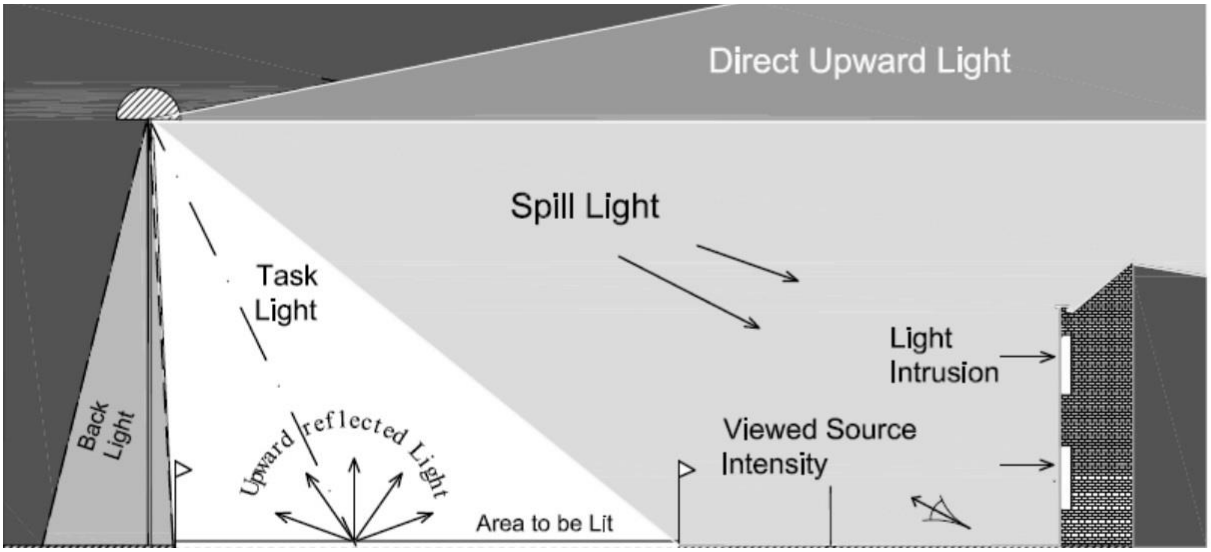

Fig. 10 Shows the different ways light pollution can occur [21]

Good design will reduce the light pollution caused and it consist of a light source, a luminaire and a method of installation. Care should be taken when selecting luminaires to ensure that their location will reduce spill light and glare to a minimum. Using specifically designed lighting equipment minimizes the upward spread of light. Keep glare to a minimum by ensuring main beam angle of all lights are directed towards potential observer not more than 70^0 as illustrated in Fig.11.

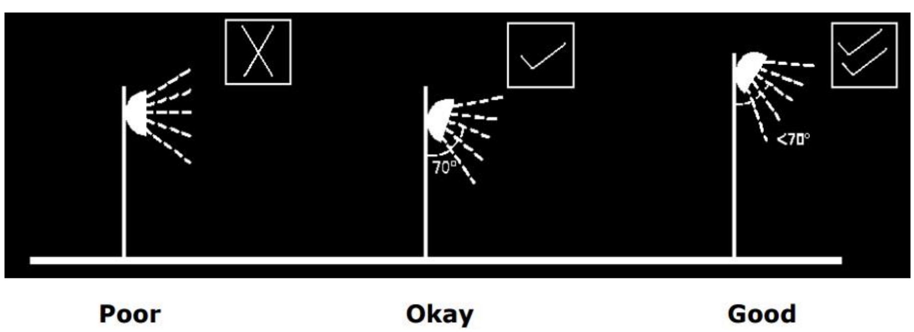

Fig. 11 Beam angles [21]

When lighting vertical structures, such as advertising signs, it is recommended to use direct light downwards whenever possible. If there is no alternative to up-lighting, use shields, baffles and louvres that will help reduce spill light. [21]

4. Photometric Diagrams and Line Spectrums

In the lighting industry photometric diagrams are essential. These diagrams tells us if the flux (the lumens or the flow of light) is going upwards, downwards or sideways.

4.1. Line spectrum of low pressure sodium lamp

I used Phillips 61025 lamp for our measurements.

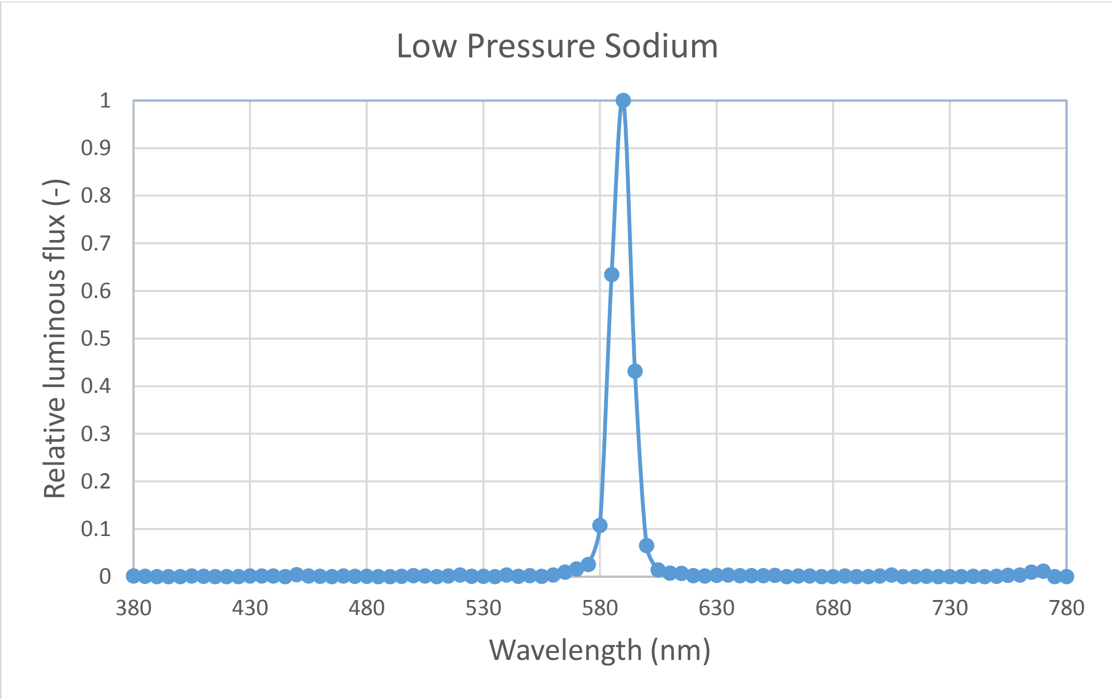

Fig. 12 Line spectrum of low pressure sodium lamp

The low pressure sodium lamp was the first sodium lamp to be developed. It is widely known for its monochromatic yellow color. The reason for this yellow spectrum is due to the presence of neon gas which lights up at low temperature and as temperature increases the sodium vaporizes which makes the lamp glow in yellow color. It is efficient, restarts immediately and lumen output does not drop with age. The major disadvantage is it has unsatisfactory color rendering [20]. From the measurements shown in Fig.12, we can observe that the highest luminance is at yellow and orange color spectrum which is between 570 to 600 nm. All other color spectrums are almost minimal.

4.2. Line Spectrum of High pressure sodium lamp

I used the Tesla SHC/400w for our measurements.

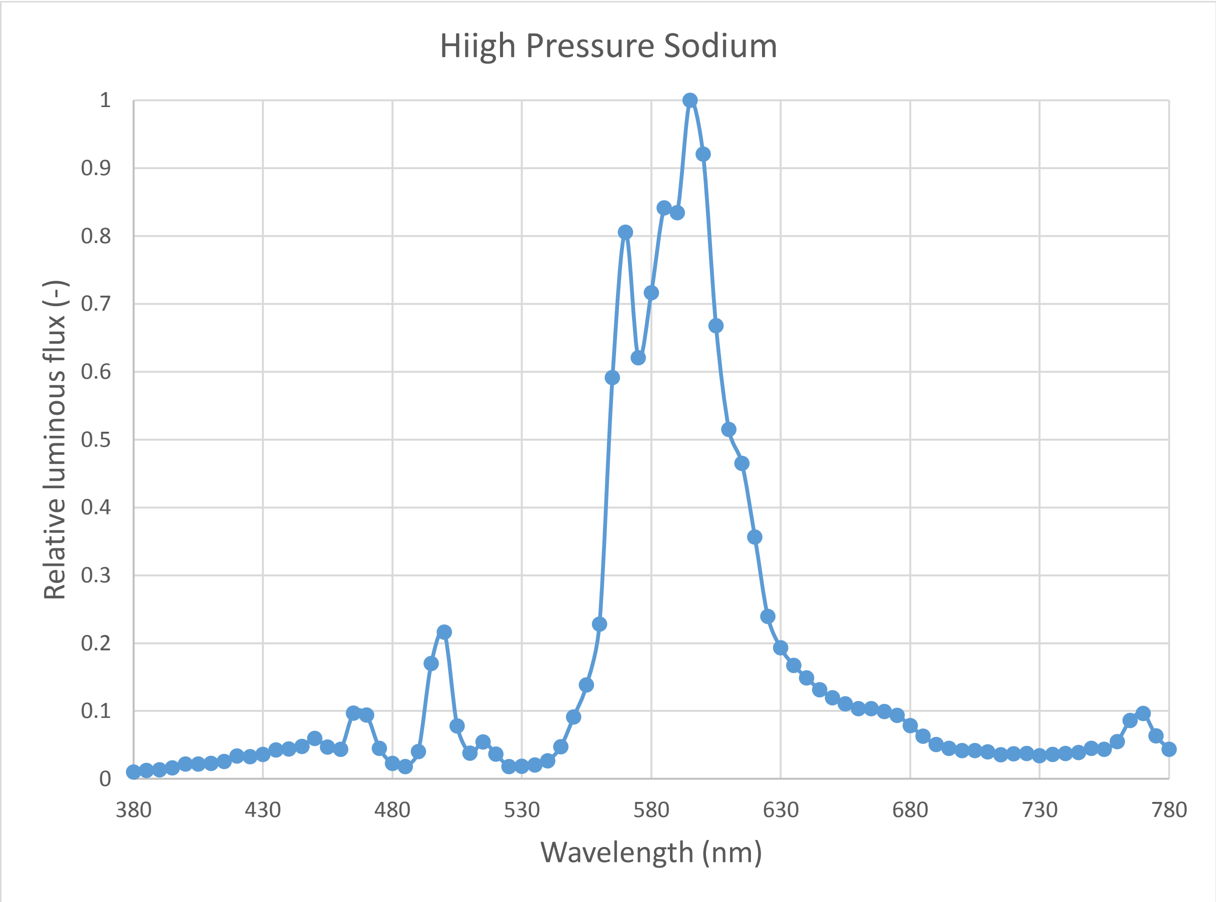

Fig. 13 Line spectrum of high pressure sodium lamp

The high pressure sodium lamps are the most widely used street lighting lamps. These lamps are an improvement over the low pressure sodium lamps. HPS lamps have a better color rendering, longer life and are smaller in size then LPS lamps. HPS lamps have a narrow arc tube which has high pressure for efficiency and they contain sodium, mercury and xenon. There is an ignitor in ballast which is used for pulse starting. The pulse starts an arc through the xenon gas which makes the lamp glow sky blue. The arc then heats mercury, which makes the lamp glow blue, and then sodium is vaporized, which makes the lamp glow orange [17]. From the measurements shown in Fig.13, we can observe that the highest luminance is at the orange spectrum at around 600 nm with an equally high luminance of green spectrum at 550 -570 nm. The blue and red spectrum is at a minimal luminance at 450 nm and 650 nm respectively.

4.3. Line spectrum of Sodium vapor lamp Osram

I used Vialox Nav-T rated 150W – 4V. It is by Iguzzuni and model BG84. I measured the line spectrum during the turning on time to the time it is completely lit. I focused on sodium vapor lamps as it is the most widely used.

We can notice as shown in Fig.14, that the line spectrum changes as the sodium vapor lamp starts up and continues to its ideal state. An amalgam of metallic sodium and mercury is present at the cooler part of the lamp. The lamp power determines the amalgam's temperature, the higher the lamp power the higher the amalgam temperature. As temperature increases the constant current and increasing voltage consumes higher energy until operating power is reached. There are 3 stages of operation – the lamp is extinguished and current does not flow, the lamp is operating with liquid amalgam in tube and lamp is operating with amalgam evaporated. First and last states are stable. [20]

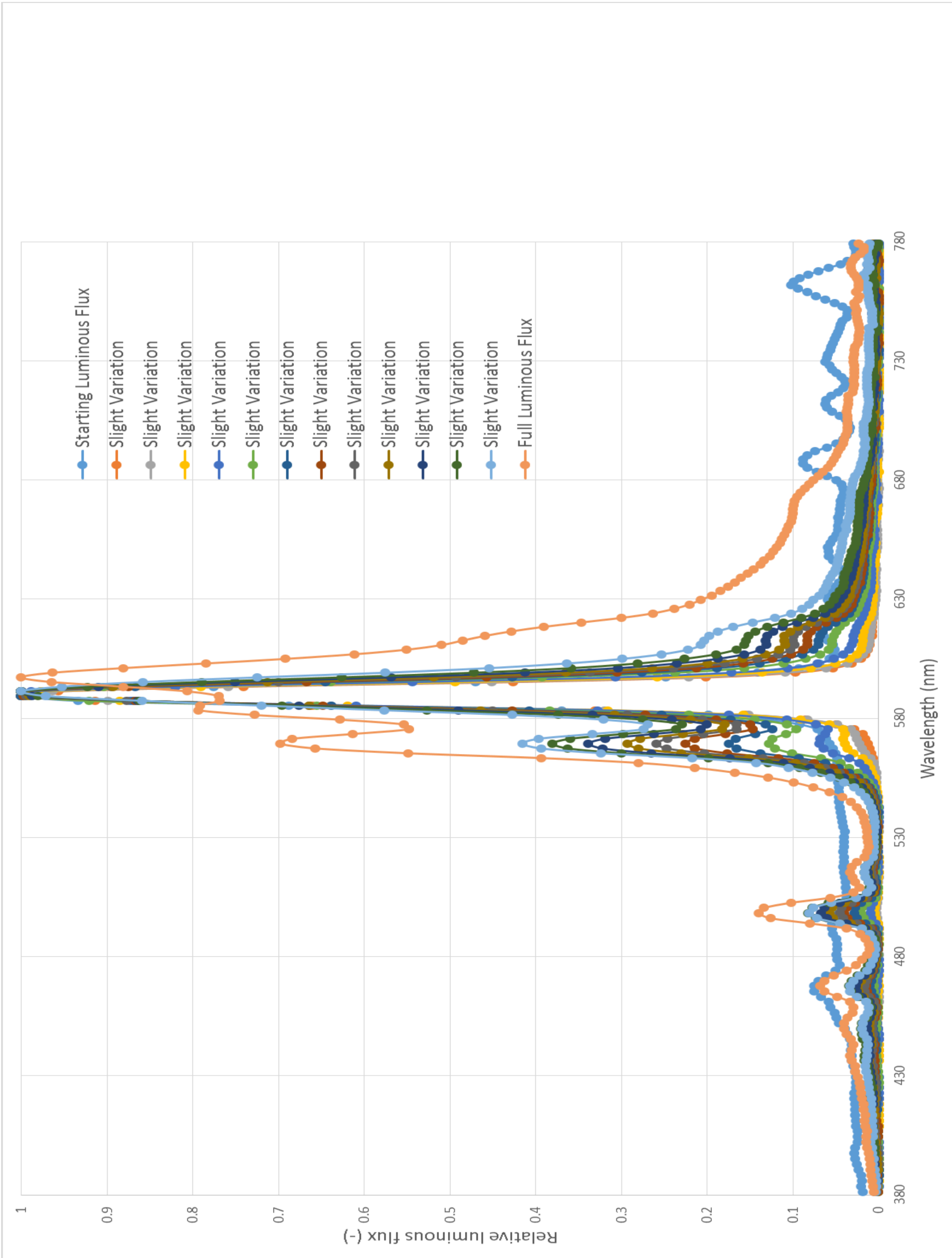

Fig. 14 Line spectrum of Osram sodium vapor lamp

4.3.1. Luminous flux vs Time

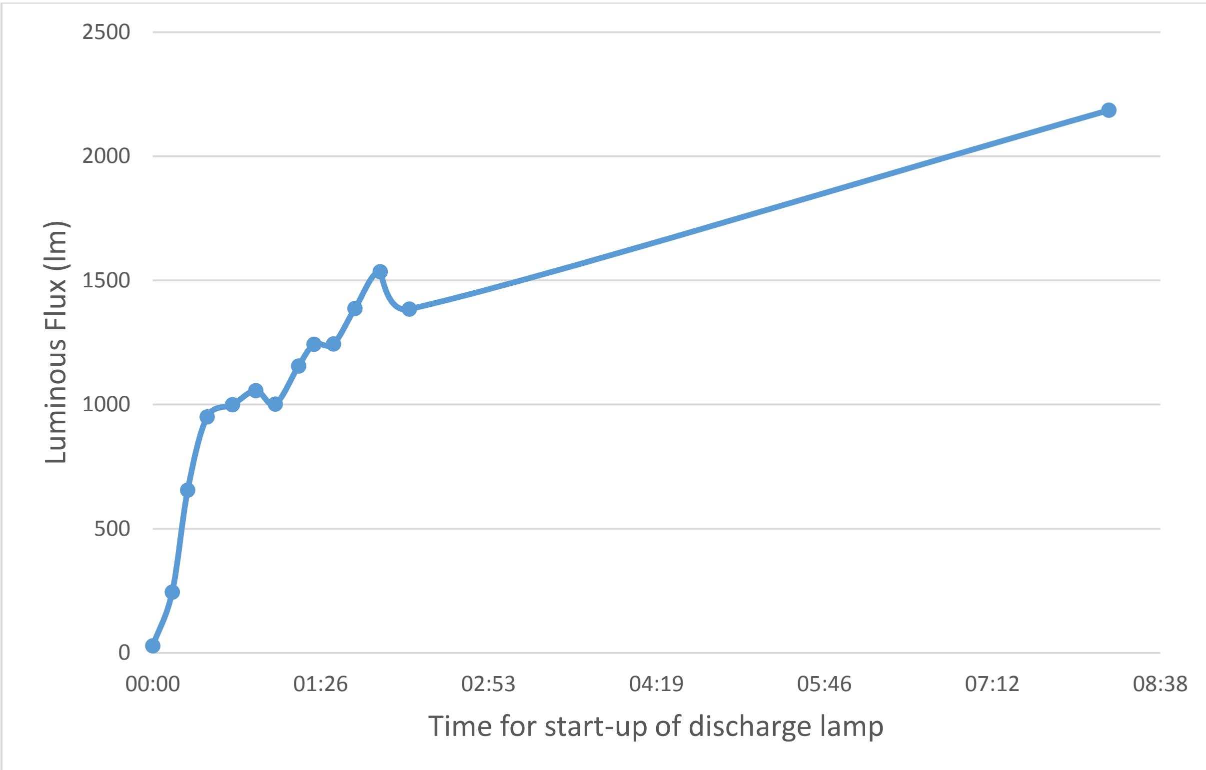

Fig. 15 Luminous flux Vs Time

As we can see the Fig.15 the luminous flux increases with time and due to the constant current and increasing voltage the flux varies slightly until it reaches 1500 lm then it drops a little before increasing to 2185 lm.

4.3.2. Color temperature vs Time

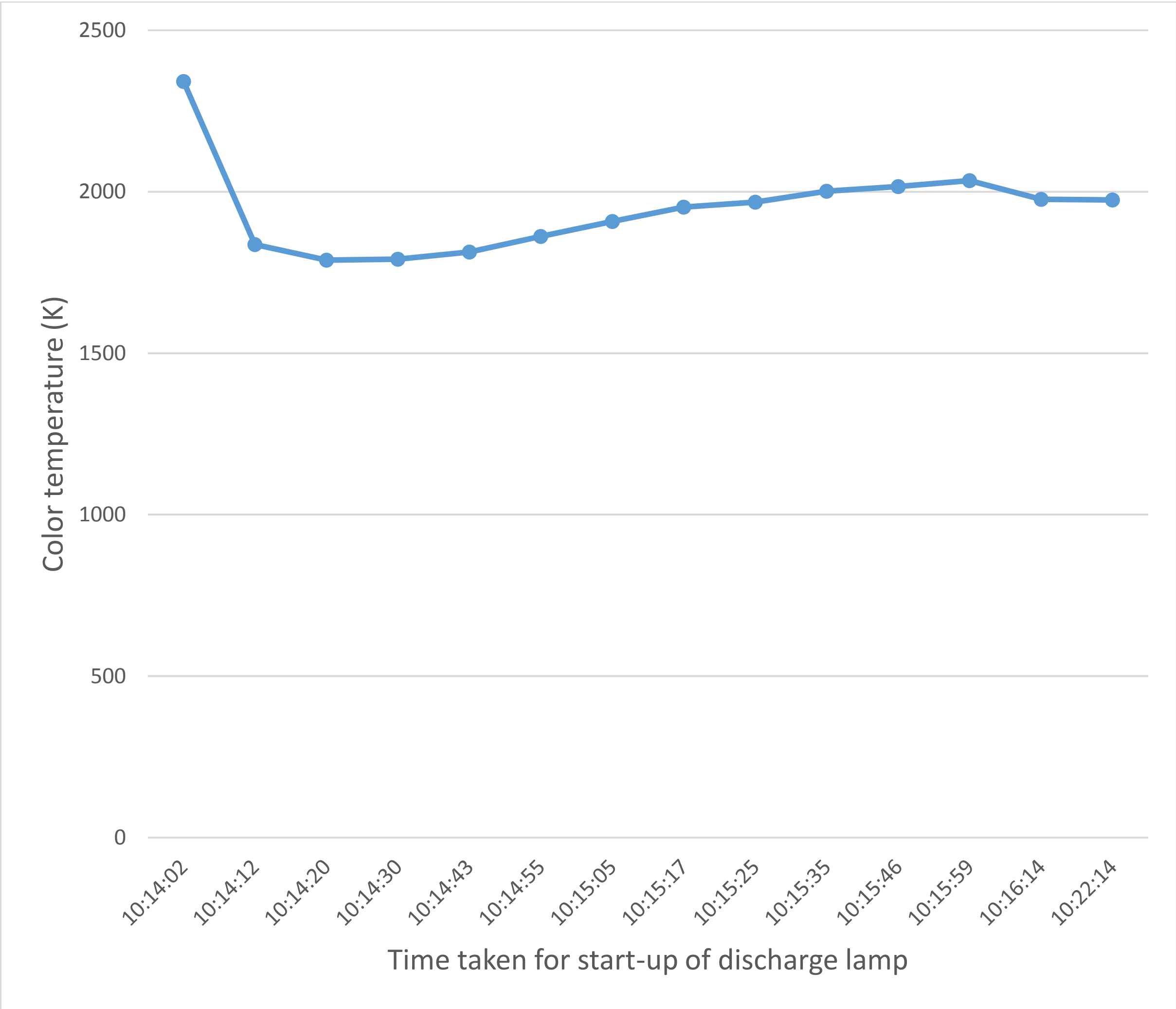

Fig. 16 Color temperature Vs Time

The color temperature starts at 2342 K then it decreases to 1837 K as the lamp stabilizes with rising temperature. As temperature increases the color temperature also increases until it stabilizes at 1975 K as depicted in Fig.16.

4.3.3. Illuminance vs Time

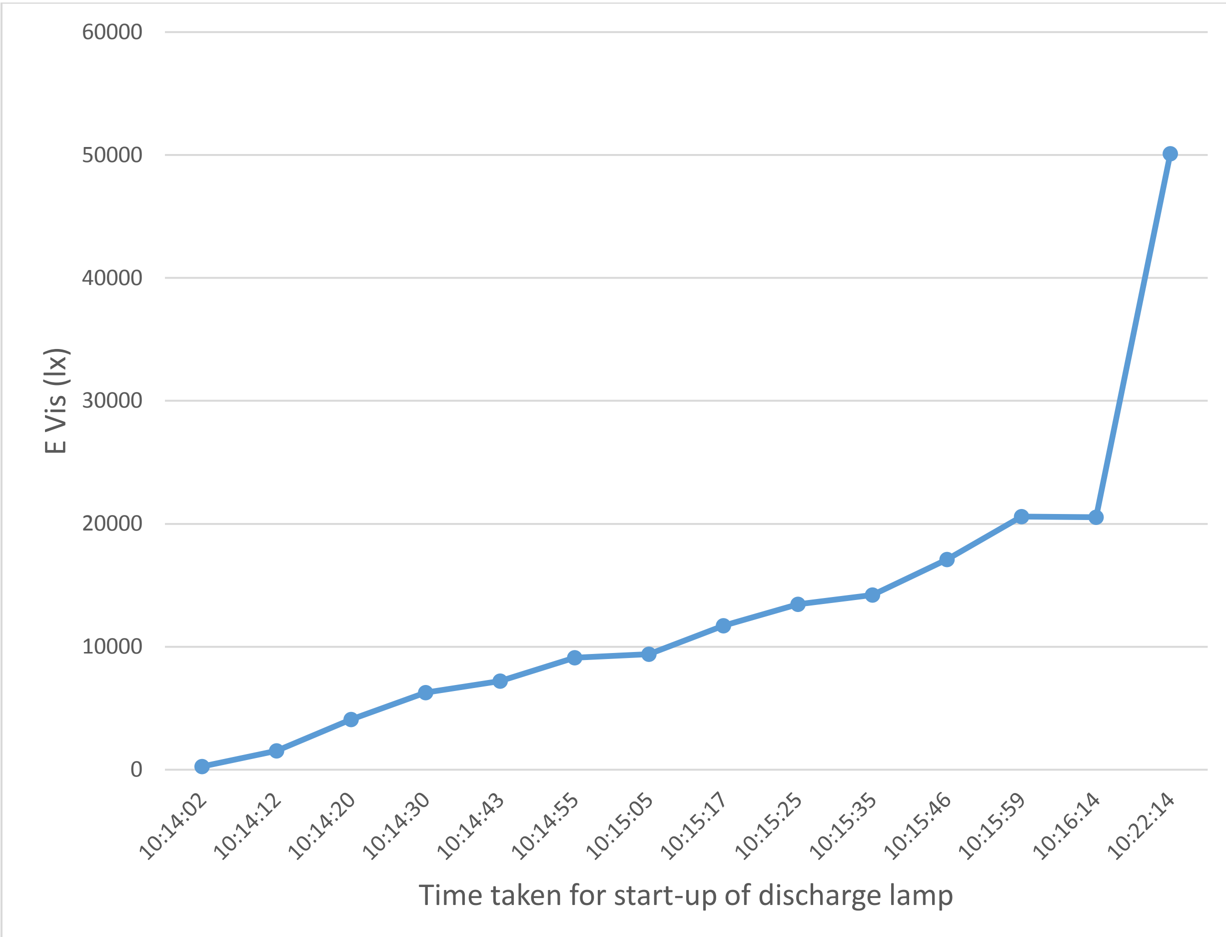

Fig. 17 Illuminance Vs Time

The illuminance increases as the temperature rises and time passes by. After 2 minutes of starting the discharge lamp there is a sudden increase of illuminance from 20548 lx to 50095 lx. This happens as the amalgam is evaporated and the lux becomes stabilized as shown in Fig.17.

4.4. Line spectrum of metal halide lamp

I used the Osram HQI-T 400W Q738 lamp for our measurements.

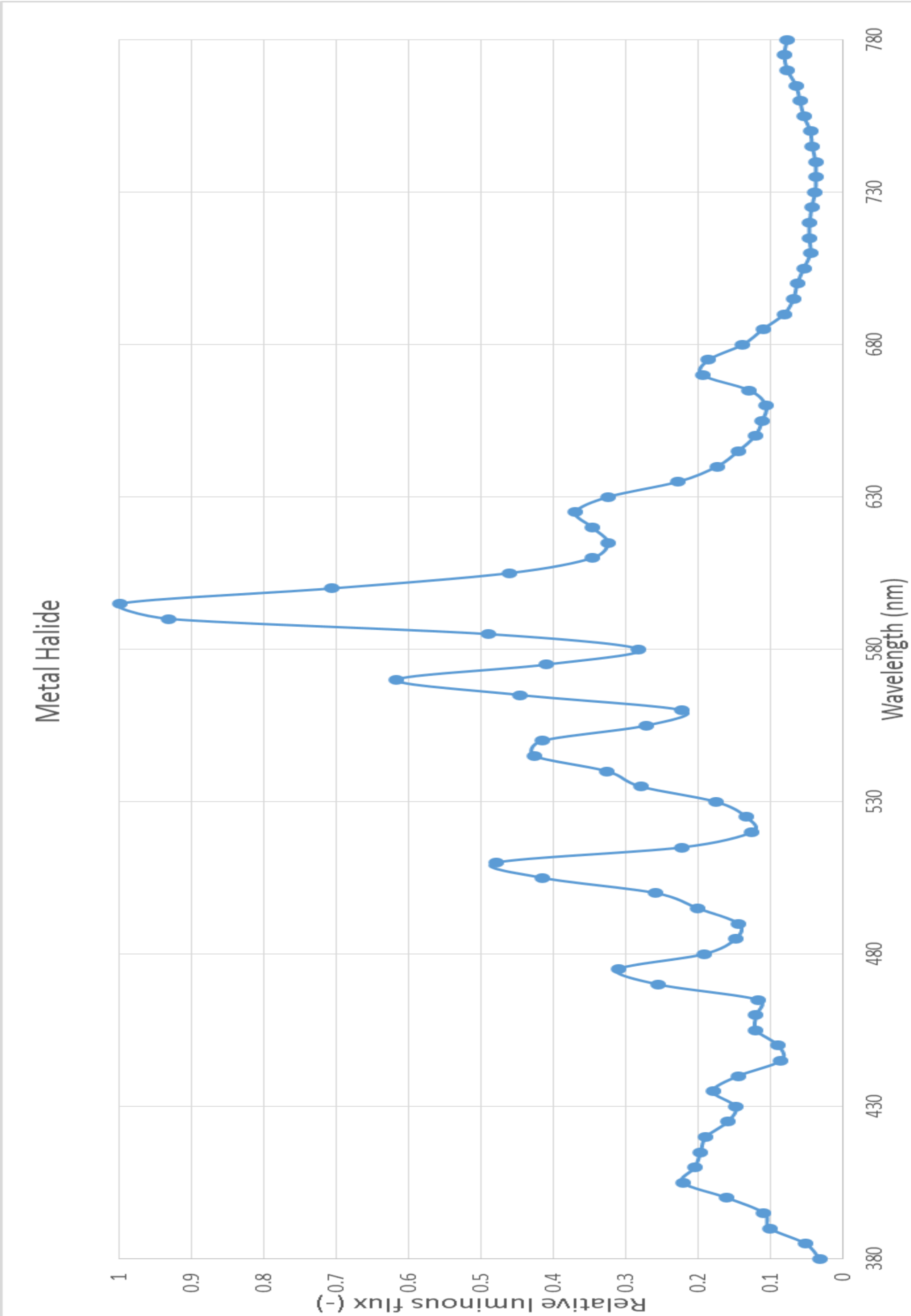

Fig. 18 Line spectrum of metal halide lamp

Metal halide lamps has arc tube which is made up of either quartz or ceramic and contains argon, mercury and MH salts. The gas in the MH arc tube must be ionized before current can flow to start the lamp. As temperature increases the materials in arc tube vaporize which emits light and UV radiation. Phosphor coat is used to diffuse the light and change lamp color properties [18]. The line spectrum of Metal halide lamps are balanced. From Fig.18, we can conclude that the highest luminance is at green which is at 550 nm. Orange and yellow colors make up major part of the spectrum at 570 to 620 nm.

4.5. Line spectrum of LED lamp U-Tron

I used Lucas III 80 with rating of 83.1W and CRI of 70.8 for our measurements.

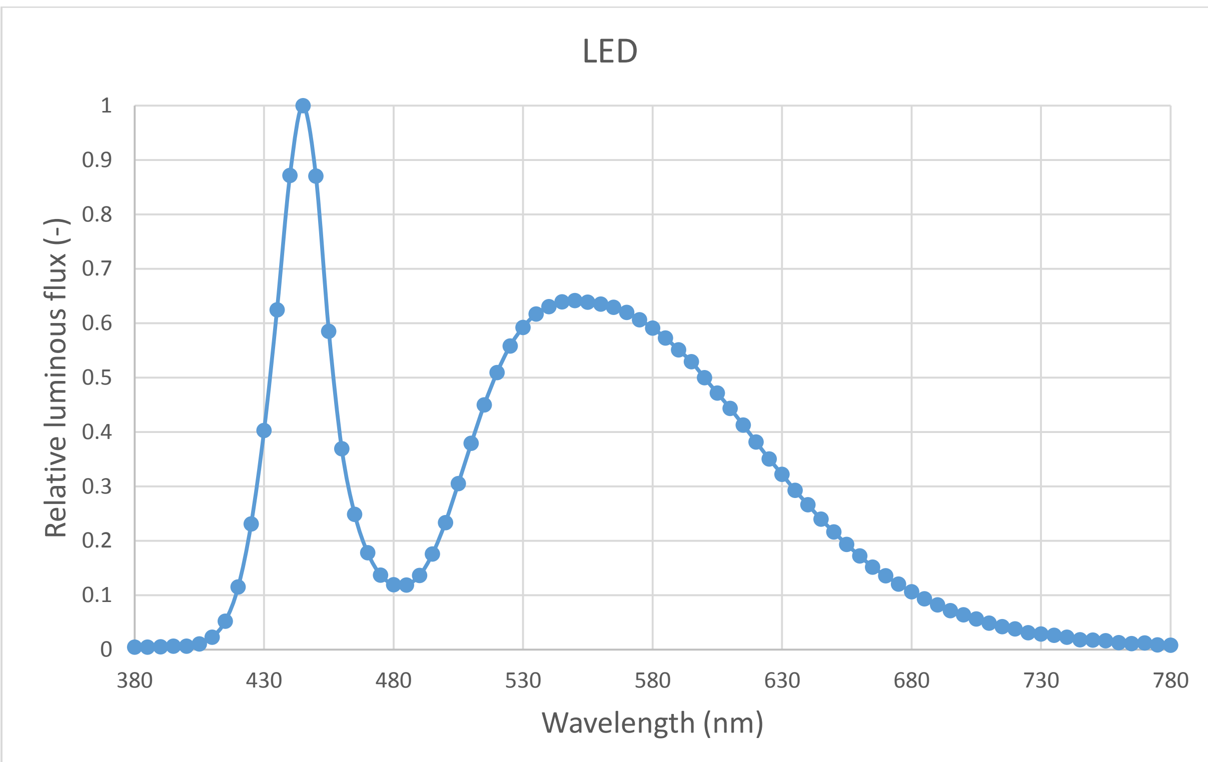

Fig. 19 Line spectrum of LED lamp U-Tron

LEDs work on the principle of electroluminescence. The electrons dissipate energy in the form of heat for silicon while electrons emit photons with germanium diodes consisting of gallium arsenide phosphide or gallium phosphide semiconductors [19]. Due to the presence of silicon and gallium the blue color spectrum is highest of any light source which is from 450 – 500 nm as shown in Fig.19. But there is also a considerable color spectrum of green, yellow and orange from 500 to 650 nm.

4.6. Line spectrum of Schreder LED lamp

I used the Nano 1/16 LED lamp rated 230W,40W/50hz for our measurements.

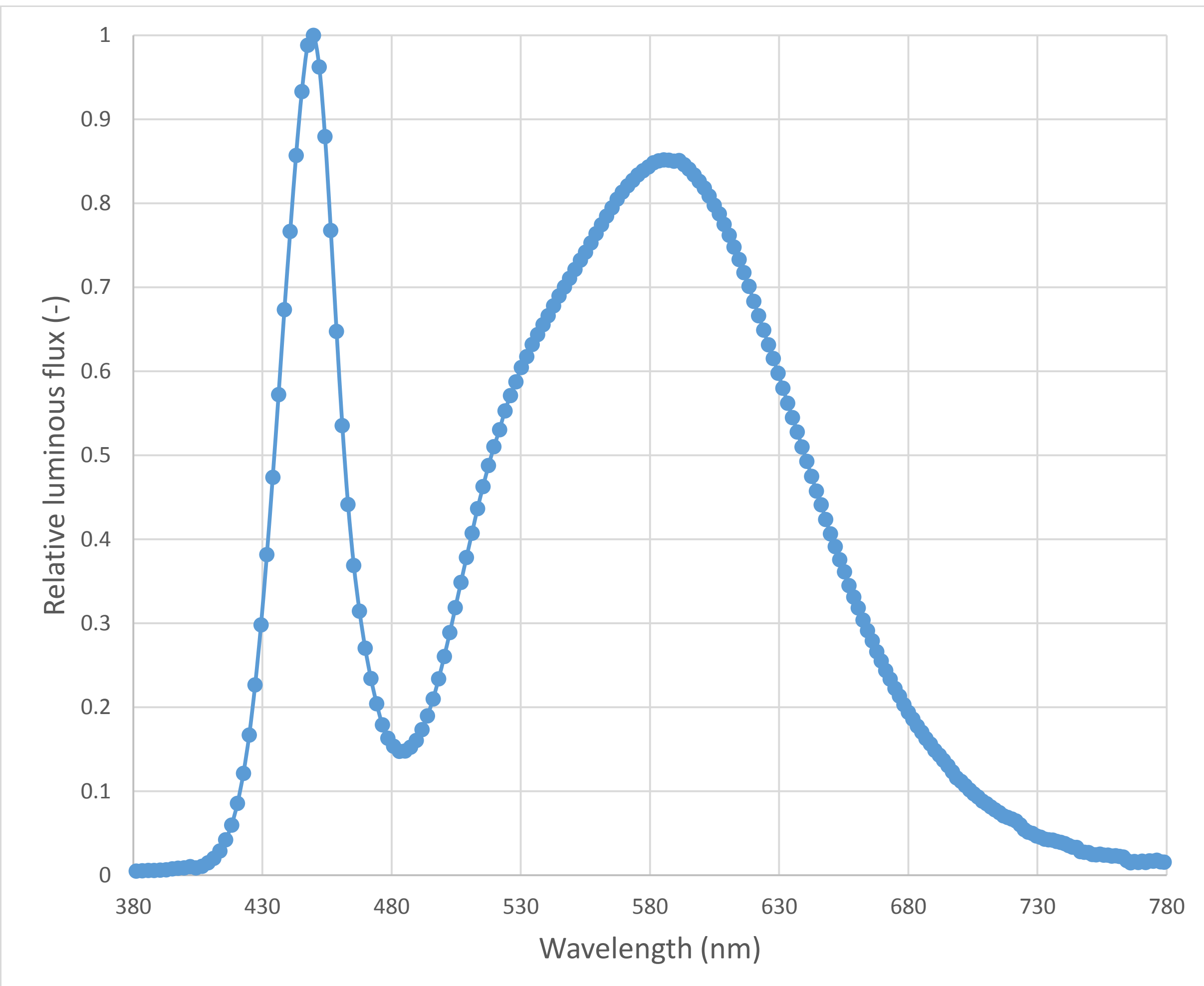

Fig. 20 Line spectrum of Schreder LED lamp

As compared to U – Tron's Lucas III LED the Schreder Nano 1/16 LED has high color spectrum and luminous flux of colors green, yellow and red as shown in Fig.20. This improvement can be attributed to the technological advancements in LEDs. The distribution of light is appropriate for road lighting as well but the high relative luminous flux of color blue is not suitable for human eyes and the environment.

4.7. C planes of U – Tron's Lucas III 80 LED

From the C plane of this LED lamp as depicted in Fig.21 we can deduce that it is inappropriate for today's road lighting. This type of distribution was common 5 years ago as these were the first LED road lights. These early LEDs weren't able to distribute light evenly. As LED technology has improved the distribution has improved too. For instance, sodium vapor lamp BG 84, which is discussed further into the thesis, has a more suitable distribution of light for road lighting.

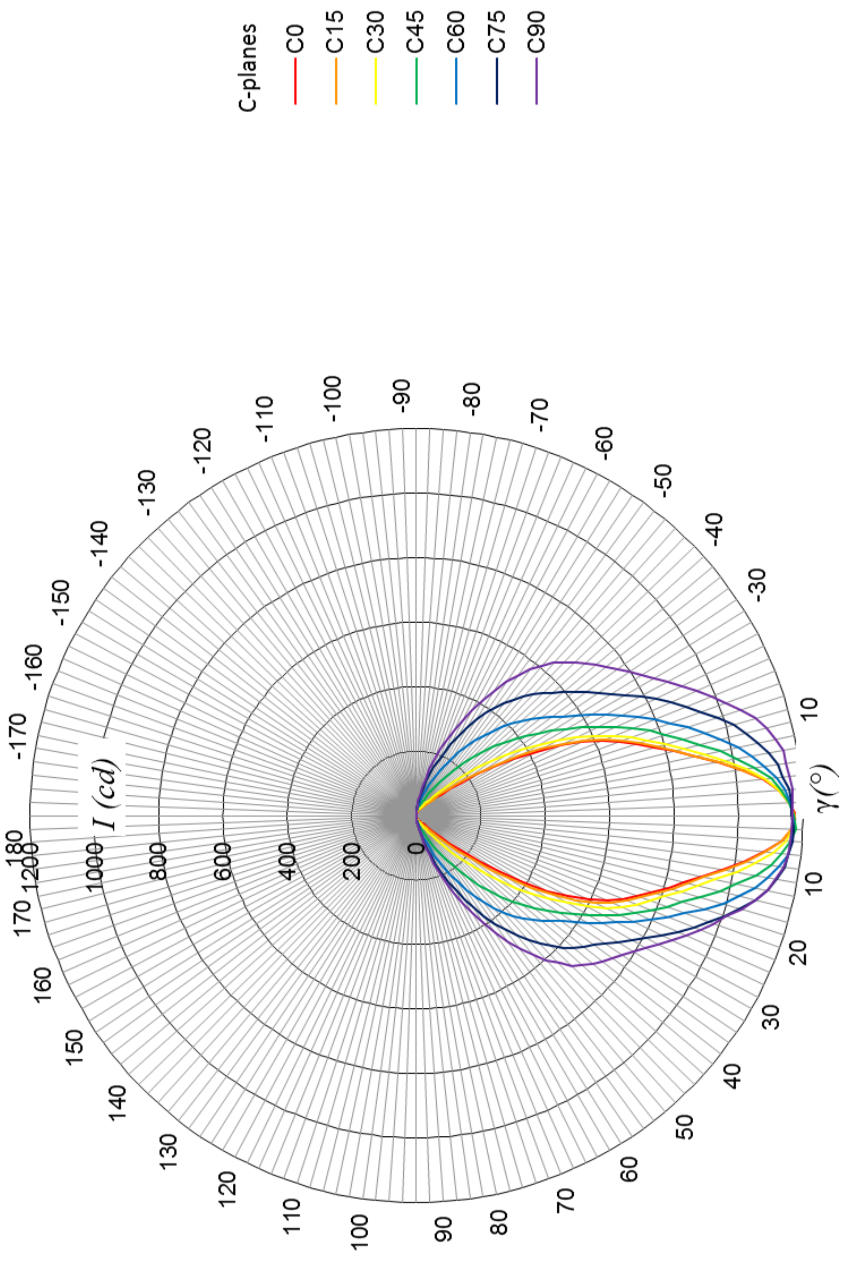

Fig. 21 C planes of U – Tron's Lucas III 80 LED

4.8. C planes of Schreder LED lamp

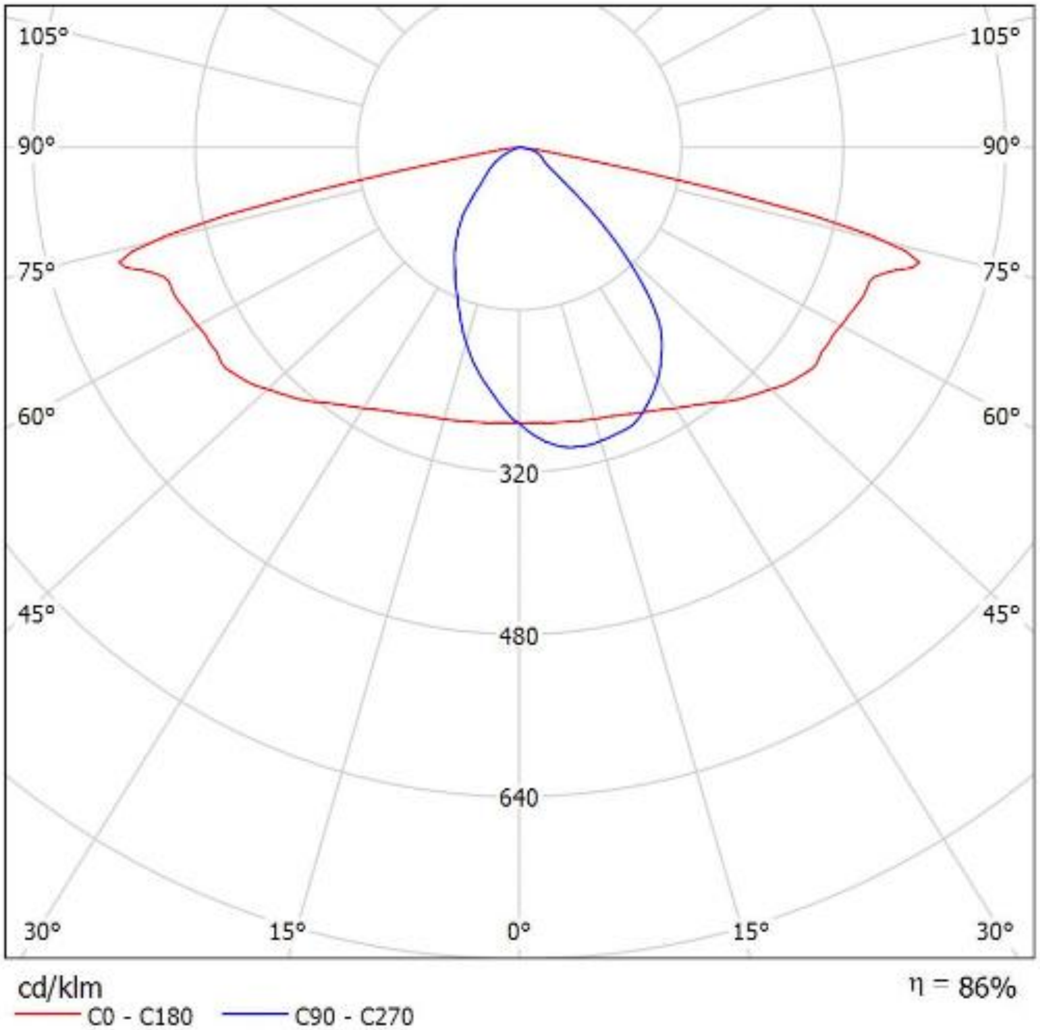

Fig. 22 C plane of Schreder Nano LED lamp

It can be noticed that the distribution of this lamp is ideal for street lighting conditions as depicted in Fig.22. I also compared Schreder Nano LED lamp with iGuzzini BG84 in DIALux program to deduce which is more ideal for street lighting. (See appendix A and B).

C plane of U-Tron (See chapter 4.7) shows a decent distribution for use in street lighting but as road standards changed this distribution is not applicable for today's use. Low pressure sodium lamps were once used for street lighting, some countries still use them because of their efficiency but it has a starting time of 5 -10 minutes and sub-par color rendering index. Low pressure sodium lamps were replaced with high pressure sodium lamps which has a better color rendering index (See chapter 2.3) and is smaller in size. Metal halide lamps is also used in street lighting for their pure white light as compared to high pressure sodium lamps. Metal halide lamps are widely used to light up sports stadiums due to their high color temperature (See chapter 2.4).

After calculating and analyzing line spectrums of traditional light sources and LEDs we can conclude that LED light sources reaches its peak between 430 – 450 nm which emits blue light. High pressure sodium lamps reaches its peak between 550 – 600 nm which emits yellow and orange light. High pressure sodium lamps are the most commonly used street lights because of their efficiency. Manufacturers and dealers of LED streetlights must notify and educate their clients about the use of LED lamps and the harmful effects when exposed to blue light. New LED lamps must emit less blue light and have less flicker to make the street lighting safe for application.

5. Future trends in street lightning

Street lightning is an important topic of discussion at the moment as it is the time of increased energy costs, stringent energy targets, reduced city budgets and emerging lighting technology, Fig. 21 shows the energy consumption of street lighting. Most cities now look towards new upcoming technology to save costs. Retrofitting new technology on to existing lighting systems can make up for illuminance requirement but it does not take into account the night time identity and character of a region.

Street lighting was first invented for personal safety and not for automobiles. As time progressed the need for automobile street lighting reduce and in the last 25 years, road deaths have halved and yet energy consumption on street lighting has increased [16]. Lighting must reevaluate the balance and become more accommodating to the needs and experiences of the people using the streetscape. The elements that need to be explored are:

- Lighting that enhances way finding which puts emphasis on quality and space not quantity and planar illuminance
- Dynamic systems that change with pedestrian flows
- Self-monitoring intelligent systems that offer incidental illuminance from retail/office space and determine if additional light is required
- Urban lighting which can scene set with interior space to connect with pedestrian needs and create a lighting impression that corresponds to the brightness of the night sky
- Lighting that encourages interaction, walking and cycling in a 24 hour society

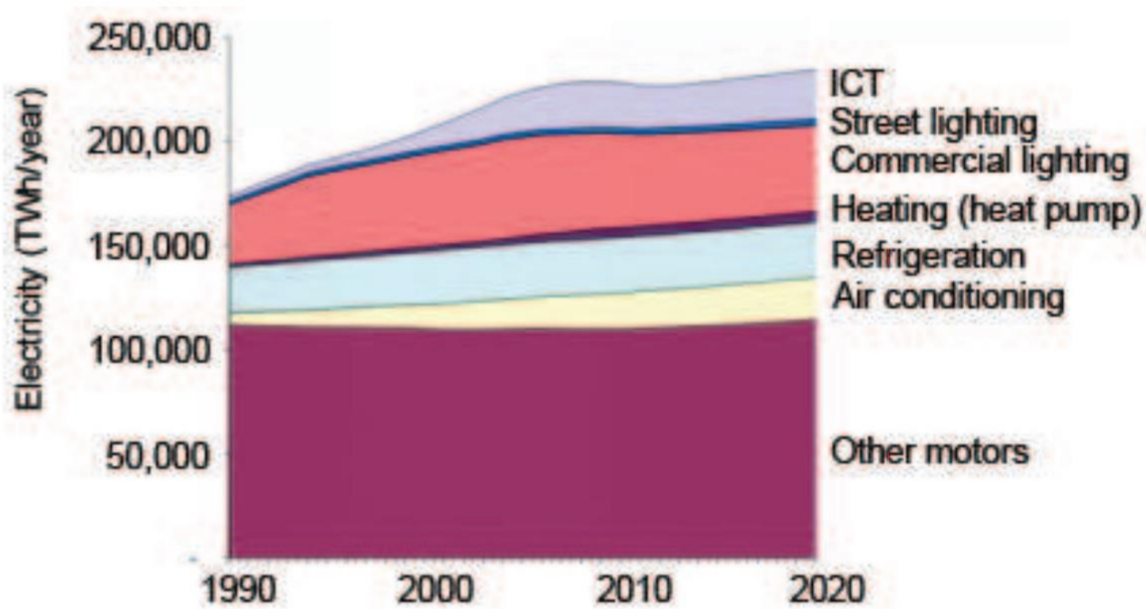

Fig. 23 Energy consumption of street lighting [16]

New approaches to urban lighting should be regulated to allow a city to reconnect with the sky above. Current lighting practices results in loss of the night sky as eye adapts to competing artificial light sources. This practice can create a vital connection to wider environment and will result in reduced sky glow and less wasted light thereby reducing light pollution.

Let us take a look at the urban lighting in Westminster which is a dynamic and diverse area of central London. It is home to Oxford Street, Mayfair, Trafalgar Square and the West End. Millions of visitors are drawn to this place and the city must ensure a vibrant experience which requires a dynamic, proactive and interactive lighting solution. Westminster realized that to meet its challenges with its existing political and financial climate, it needs to employ latest Central Management System (CMS) technologies to optimize its lighting systems. After an extensive assessment of available alternatives, wireless systems controlling the Philips Cosmopolis lamp were chosen as best option. Harvard LeadNut system was identified as a system which best met the stringent requirements that the city council demanded.

The plan was to retrofit current luminaires but in some cases to replace older equipment. It also aimed to enhance highway illumination by using improved optics designed for Cosmopolis lamp when needed. The aim of the Smart Light project was to reduce revenue maintenance cost by increasing the current 2 years lamp replacement cycle to 4 year cycle. Even cleaning and routine maintenance cycles will be changed and operate around 4 year cycles. The Smart Light project also aims to reduce revenue energy costs and improve overall service delivery by:

- Removal of night scout and integration of the CMS with the job ordering system which by creating automatic auditing process will report light is out until resolved.
- Positive and negative asset operational status
- Predictive lamp failure resulted by monitoring the voltage and planned maintenance

Through Smart Light the council was expecting to realize energy saving up to 40% and reduce 1858 tonnes of carbon footprint. [16]

One of the new technologies in street lighting systems is APANET's GLC (Green Light Controller). APANET is a producer of smart lighting control systems based on LonWorks technology. GLC's are a smart driver controlling lamps in the streets, parks, squares etc. It enables full control over lighting installation, i.e.:

- Individual street lamps control which can be either manual or automatic on/off powering as well as lamp power control
- Calculating electricity consumption for individual lamps, cluster of lamps or additional equipment powered by the same power source
- Street lamps operation monitoring in the event of malfunction the system can notify an operator or service teams for the need of intervention
- Detection of unauthorized lamp housing opening including notification to appropriate services
- Using existing power lines and possibility changing luminance to the needs and requirements [22]

GLC reduces lighting parameters whenever possible, for instance when traffic is low or when weather visibility is good. The system is able to reduce lighting parameters or completely switch off some lamps. It gives a significant reduction in electricity consumption and therefore contributes to savings. Current installation in Oslo confirms savings up to 70%.

The infrastructure consists of GLC's, GreenLight server concentrator and optional SCADA system. GLC is installed directly into the lamp, either in lamp post or casing and control ballasts which adjust luminance. It can be done automatically with use of data registered by traffic and weather sensors, as well as manually by a system operator. GLC also saves and sends data regarding electricity consumption, lamp uptime and possible malfunction.

The future of street lighting is being realized with application of Internet of Things (IoT). There are various potential applications which are yet to be utilized by the lamp posts which can be used for additional applications such as traffic optimization by using movement detection sensors, public Wi-Fi provision, electric vehicle charging and air pollution detection. The future LED lamps must take into account the harmful effects of blue light (See chapter 2.6) and make sure to reduce blue light and flicker emitting from the LED. Even though the effects of blue light is known there is nothing much happening to reduce it. Governmental agencies must enforce legislations and laws to limit the sale and use of LEDs with high blue light emission to keep the future street lights safe for use.

6. Conclusion

LED lights are being preferred over traditional light sources in recent times as they have many advantages. LEDs consume less electricity, they have longer life span and turn on instantaneously. LEDs are smaller in size, emit light in specific direction reducing amount of reflectors required and emit minimum amount of heat. LEDs affect the circadian rhythm of humans as the excess blue light can damage photoreceptor cells, because blue light reduces melatonin production in pineal gland. Despite the fact they save energy, LEDs create worse night time glare than conventional lighting. Blue light can cause discomfort which can decrease visual acuity while creating road hazards. As we know the harmful effects of excess blue light and exposure of flicker it is recommended that new LEDs emit light at wavelength 470 – 480 nm over the current LEDs which emit light at wavelength < 450 nm.

Sky glow, glare and obtrusive lighting cause light pollution. It creates a smog like effect which blocks out the night sky and this can cause environmental and physiological problems. In order to reduce light pollution care must be taken while designing the lighting system. It is recommended to use luminaries which keeps the spread of light downwards to avoid upward spread of light and keeping the beam angle less than 700 to keep the glare to the minimum.

I measured the line spectrums of different light sources such as low pressure sodium lamp, high pressure sodium, metal halide lamp and LEDs. I also measured C plane of U Tron LED to see the distribution of light and concluded that it not feasible for use in street lighting as it does not have a good light distribution. High pressure sodium lamps are the most widely used lamps for street lighting as it is efficient, smaller in size and has a good color temperature while lacking in color rendering index but updated version called White SON high pressure sodium lamp has color temperature of 2700 K and Color rendering index at 85. In recent years, sodium lamps are increasingly being replaced by LEDs which emits high amounts of blue light and causing more glare than sodium lamps.

Future of street lighting is being integrated with Internet of Things where everything is connected to internet. Lamp posts of street lighting could have potential for additional applications like traffic optimization, air pollution detection and Wi-Fi. In future governmental agencies must enact laws and regulations limiting the use of LEDs with high emission of blue light. Local governments must run public awareness campaign to educate the masses about the harmful effects of blue light. Manufacturers should also invest in making LEDs less harmful and safe for public application.

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Appendix A: DIALux calculations of Schreder NANO LED

Project 1

DIALux

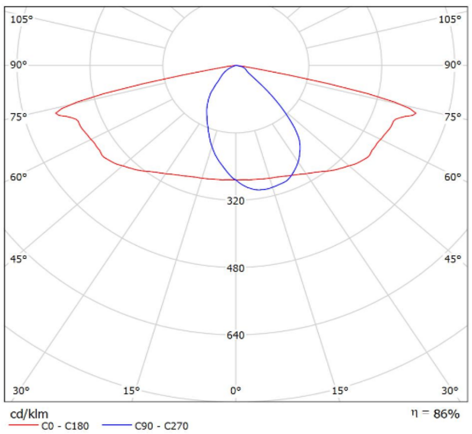
24.05.2017

Operator
Telephone
Fax
e-Mail

SCHREDER NANO 2 LED 5102 16 LEDS 700mA NW 343332 / 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: 44 76 96 100 86

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

Operator
Telephone
Fax
e-Mail

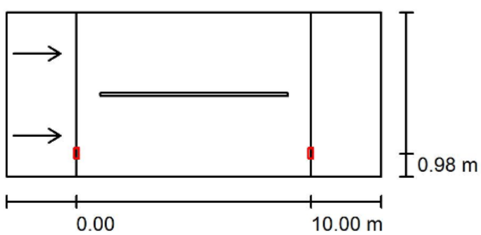
NANO / Planning data

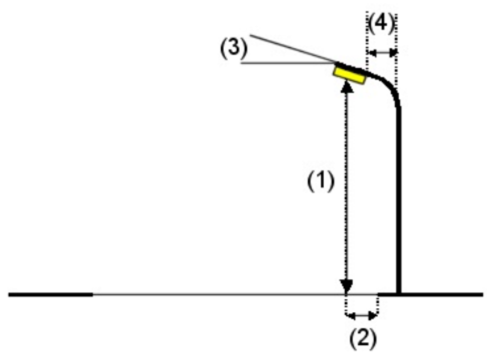
Street Profile

Roadway 1 (Width: 7.000 m, Number of lanes: 2, tarmac: R3, q0: 0.070)

Light loss factor: 0.80

Luminaire Arrangements





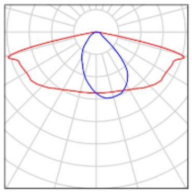
Luminaire:	SCHREDER NANO 2 LED 5102 16 LEDS 700mA NW 343332		
Luminous flux (Luminaire):	3602 lm	Maximum luminous intensities	
Luminous flux (Lamps):	4173 lm	at 70°:	526 cd/klm
Luminaire Wattage:	36.0 W	at 80°:	450 cd/klm
Arrangement:	Single row, bottom	at 90°:	5.53 cd/klm
Pole Distance:	10.000 m	Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.	
Mounting Height (1):	6.168 m		
Height:	6.000 m	Arrangement complies with glare index class D.4.	
Overhang (2):	0.999 m		
Boom Angle (3):	5.0 °		
Boom Length (4):	1.635 m		

Operator
Telephone
Fax
e-Mail

NANO / Luminaire parts list

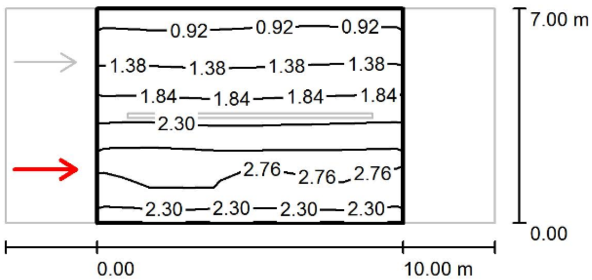
SCHREDER NANO 2 LED 5102 16 LEDS 700mA NW 343332
Article No.:
Luminous flux (Luminaire): 3602 lm
Luminous flux (Lamps): 4173 lm
Luminaire Wattage: 36.0 W
Luminaire classification according to CIE: 100
CIE flux code: 44 76 96 100 86
Fitting: 1 x 16 LEDS 700mA NW (Correction Factor 1.000).

See our luminaire catalog for an image of the luminaire.



Operator
Telephone
Fax
e-Mail

NANO / Valuation Field Roadway 1 / Observer 1 / Isolines (L)



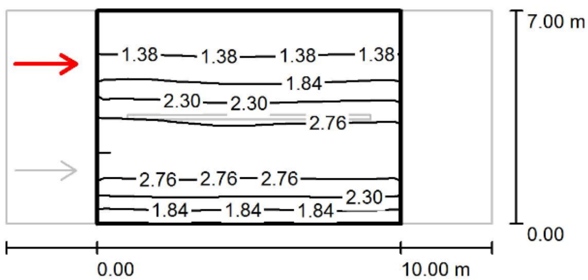
Values in Candela/m², Scale 1 : 200

Grid: 10 x 6 Points
Observer Position: (-60.000 m, 1.750 m, 1.500 m)
tarmac: R3, q0: 0.070

	L_{av} [cd/m²]	U0	Ul	TI [%]
Calculated values:	2.00	0.44	0.98	10
Required values according to class ME1:	≥ 2.00	≥ 0.40	≥ 0.70	≤ 10
Fulfilled/Not fulfilled:	✓	✓	✓	✓

Operator
Telephone
Fax
e-Mail

NANO / Valuation Field Roadway 1 / Observer 2 / Isolines (L)



Values in Candela/m², Scale 1 : 200

Grid: 10 x 6 Points
Observer Position: (-60.000 m, 5.250 m, 1.500 m)
tarmac: R3, q0: 0.070

	L_{av} [cd/m²]	U0	Ul	TI [%]
Calculated values:	2.17	0.43	0.95	9
Required values according to class ME1:	≥ 2.00	≥ 0.40	≥ 0.70	≤ 10
Fulfilled/Not fulfilled:	✓	✓	✓	✓

Appendix B: DIALux calculations of iGuzzini BG84

Operator
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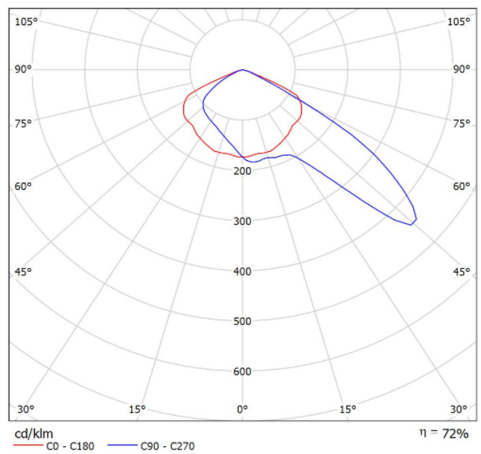
iGuzzini illuminazione S.p.A BG84 (P1)+L048 Optical assembly - 100W HST/HIT-CE - electromagnetic control gear - street optic - H.P. sodium vapour lamp HST 100W E40 2000 K / Luminaire Data Sheet

Luminous emittance 1:

See our luminaire catalog for an image of the luminaire.



Luminaire classification according to CIE: 100
CIE flux code: 38 80 99 100 72

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

Operator
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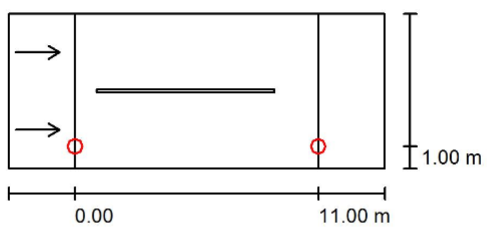
BG84 / Planning data

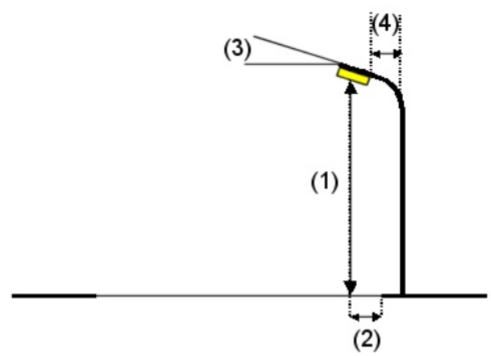
Street Profile

Roadway 1 (Width: 7.000 m, Number of lanes: 2, tarmac: R3, q0: 0.070)

Light loss factor: 0.80

Luminaire Arrangements





Luminaire:	iGuzzini illuminazione S.p.A BG84 (P1)+L048 Optical assembly - 100W HST/HIT-CE - electromagnetic control gear - street optic - H.P. sodium vapour lamp HST 100W E40 2000 K		
Luminous flux (Luminaire):	7179 lm	Maximum luminous intensities	
Luminous flux (Lamps):	10000 lm	at 70°:	281 cd/klm
Luminaire Wattage:	117.0 W	at 80°:	11 cd/klm
Arrangement:	Single row, bottom	at 90°:	0.00 cd/klm
Pole Distance:	11.000 m	Any direction forming the specified angle from the downward vertical, with the luminaire installed for use.	
Mounting Height (1):	6.184 m		
Height:	6.000 m	No luminous intensities above 90°.	
Overhang (2):	1.000 m	Arrangement complies with luminous intensity class G6.	
Boom Angle (3):	0.0 °		
Boom Length (4):	1.650 m	Arrangement complies with glare index class D.6.	

Operator
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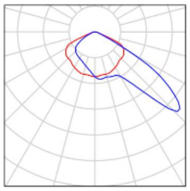
e-Mail

BG84 / Luminaire parts list

iGuzzini illuminazione S.p.A BG84 (P1)+L048
Optical assembly - 100W HST/HIT-CE - electromagnetic control gear - street optic - H.P. sodium vapour lamp HST 100W E40 2000 K
Article No.: BG84 (P1)+L048
Luminous flux (Luminaire): 7179 lm
Luminous flux (Lamps): 10000 lm
Luminaire Wattage: 117.0 W
Luminaire classification according to CIE: 100
CIE flux code: 38 80 99 100 72
Fitting: 1 x HST E40 100W (Correction Factor 1.000).

See our luminaire catalog for an image of the luminaire.



Operator
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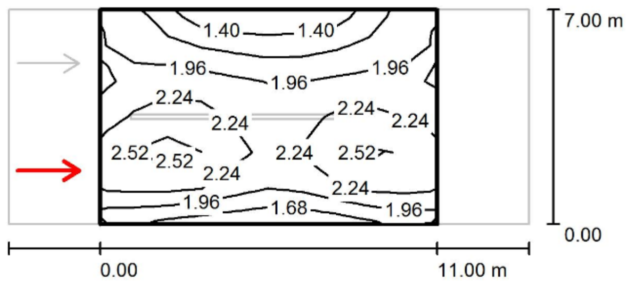
BG84 / Valuation Field Roadway 1 / Observer 1 / Isolines (L)



Values in Candela/m², Scale 1 : 200

Grid: 10 x 6 Points
Observer Position: (-60.000 m, 1.750 m, 1.500 m)
tarmac: R3, q0: 0.070

	L_{av} [cd/m²]	U0	Ul	TI [%]
Calculated values:	2.06	0.63	0.81	2
Required values according to class ME1:	≥ 2.00	≥ 0.40	≥ 0.70	≤ 10
Fulfilled/Not fulfilled:	✓	✓	✓	✓

Operator
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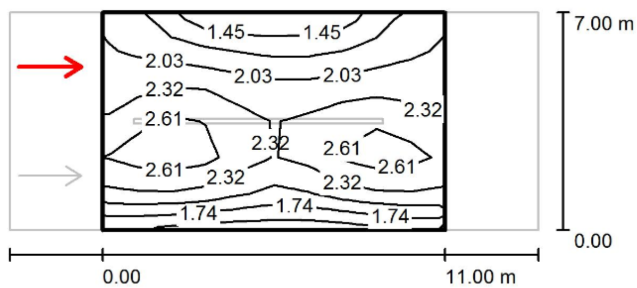
BG84 / Valuation Field Roadway 1 / Observer 2 / Isolines (L)



Values in Candela/m², Scale 1 : 200

Grid: 10 x 6 Points
Observer Position: (-60.000 m, 5.250 m, 1.500 m)
tarmac: R3, q0: 0.070

	L_{av} [cd/m²]	U0	Ul	TI [%]
Calculated values:	2.16	0.62	0.89	4
Required values according to class ME1:	≥ 2.00	≥ 0.40	≥ 0.70	≤ 10
Fulfilled/Not fulfilled:	✓	✓	✓	✓