Illuminance and Luminance for LED Street Light Optic Designs: Comparison between Big Lens and Small Lens

Witoon Prommee and Napaporn Phuangpornpitak

***Abstract*— This paper presents the study of illumination and luminance for LED Street light to compare big lens and small lens. For big lens, a large size len covers group of LED arrays. In small lens, a LED cluster is contained. Beam angle of small lens is wider than beam angle of big lens with I shape. As a result, its light distribution is better than big lens. Three indices including illuminance, luminance, and uniformity of illumination indicate safety and driver's comfortable vision. Contribution of this paper is comparison between big lens and small lens leads which both base on the I shape lens to decide optimal LED Street light placement. The LED Street light without traffic island case bases on Thai department of highway standard. To find optimal LED street light placement, the 70 watt, 120 watt, and 180 watt LED street light are simulated on four types of street including street width 8 m, 10 m, 12 m, and 15 m luminaire spacing 30 m, 35 m, and 40 m by DIALux program. From simulated results, small lens have more lighting performance than big lens. Furthermore, LED Street light with small lens can give better average illuminance, average luminance, and light uniformity than Thai street light highway standard.*

***Keywords*— LED street light placement, optical lens, Thai Department of Highway Lighting Standard.**

1. INTRODUCTION

In Thailand, the conventional street lighting uses High Intensity Discharge lamp (HID) which has High Pressure Sodium lamp (HPS), Metal Halide lamp and High-pressure Mercury Vapor lamp (HQV). They usually give efficacy (η) of light about 100 lm/watt, 75 lm/watt, and 50 lm/watt, and color rendering index (CRI) about 23, 60 and 50 respectively. According to Thailand Long-Term Load Forecasts Report [1], public lighting load including street light is the important factor which can increase the electricity energy consumption in model forecast of Metropolitan Electricity Authority (MEA) and Provincial Electricity Authority (PEA) system. As a reason, the energy saving becomes a primary policy. Light emitting diode (LED) is an energy saving light source which is selected in the case of HID streetlight replaced with LED streetlight [2].

In comparison with traditional street lighting, light emitting diodes (LEDs) give not only low power consumption but also high CRI so that optic researchers focus on LEDs technologies intensively. For instances, optical design of a freeform total internal reflection (TIR) lens for LED Street light is shown in ref [3, 4]. TIR lens can give high efficiency and a rectangular light pattern which covers the street and without distributions of neighbor residents. However, lens still are used for only one street size. Ref [5] develops a series of high brightness LED street lamps to maintain good light pattern on the road. A low loss optical reflector is designed to be 6 module LED for 8-10 m street to improve the illumination uniformity. However, the zebra effect is not considered. Ref [6] proposes Butterfly lens which are large size and can contain double-cluster LEDs. They give a good light pattern and the optical utilization factor about 43.8%, the uniformity is around 1/2.7. However, light pattern of Butterfly lens are limited on road width 10 m and spacing length 30 m. In ref [7], a cluster of LEDs with TIR lens are covered with a micro lens sheet which controls light direction only into the street. However, luminaire spacing is too short (21.5 m) for 114 watt LED. Double freeform surfaces (DFS) lens are designed by Snell's law [8]. For optimize the lens design, optical performance of lens is analyzed by Monte Carlo method. DFS lens give better illuminance uniformity than traditional lens. However, they are not tested on road sides.

For comparing HID and LED streetlight in ref [9, 10], there are five comparative indices including luminous efficacy, optics, correlated color temperature (CCT), and CRI in ref [9]. LED streetlight gives better all indices than HID. For instances, 66 watt LED has luminous efficacy 76 lm/watt, CCT 4,500 0K, CRI 75. On the other hand, 100 watt HID has luminous efficacy 53 lm/watt, CCT 2,100 0K, CRI 22. In comparing HID and LED optics, the HID lamp is a single large point source whose light is lost or uncontrolled but LEDs is the small point source whose light is controlled very little waste. Implementation on LED road lighting in Bangkok is proposed [10]. HID and LED streetlight are compared by lighting performance (average illuminance, uniformity) and electrical performance (power factor, input power). HIDs including HPS 250 watt and HQV 125 watt lamps are able to be replaced on three road types of MEA by 140 watt and 55 watt LED. Moreover, LEDs give better power factor than HPS and HQV. However, Thai department of highway lighting standard including four street types is not considered and 55 watt and 140 watt

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LEDs give lower uniformity than the standard criteria of MEA.

In this paper, LED Street light with big lens and small lens are compared on Thai department of highway lighting standard 2011, which presents three indices including illuminance, luminance, and uniformity of illumination. In section 2, the street lighting standard and installation requirements including four street types are set in Table 1 and Table 2. Moreover, illuminance, luminance, and uniformity calculation are expressed. The section 3 composes of physical form and polar light form of luminaire with big lens and small lens. For experiment and simulation results in section 4, big lens including O shape, I shape, oval shape, and U shape give different light pattern. DIALux program calculates illuminance, luminance, and uniformity of LED Street light with big lens and small lens to compare to Thai lighting standard for solving optimal LED Street light placement including LED watt size and lens. All results will be summarized in Section 5.

2. STREET LIGHTING REQUIRMENT

2.1 Street lighting requirement for department of Thai highway

Illuminance of street light requirement depends on street classification and area types shown in Table 1.

Table 1. Illuminance street light standard for department of Thai highway (2011)

Street Classification	Average Illuminance (lux)		
	Central-Urban	Sub-Urban	Rural Areas
High grade motorways	21.5	15.0	10.7
Main routes	21.5	13.0	9.7
Secondary routes	13.0	9.7	6.5
Local roads	9.7	6.5	2.1
At junction	21.5	21.5	15.0

Department of rural highway had designed street light standard for main routes of rural areas following as

- Illuminance, $E_{av} \geq 9.7$ lux
- Luminance, $L_{av} \geq 0.75$ cd/m^2
- Illumination uniformity
  $E_{min} / E_{av} \geq 1 / 2.5$ or 0.40
  $E_{min} / E_{max} \geq 1 / 6$ or 0.17

2.2 Street lighting installation requirement for Department of Thai Highway

For the street light without traffic island case, there are four street types which have different road sizes (8 m, 10 m, 12 m ,and 15 m) with 150 watt HID of luminaire spacing 30 m and 250 watt HID of spacing 40 m, 400 watt HID of spacing 35 m shown in Table 2.

Table 2. The installation of street light without traffic island case for department of Thai highway

Street Type	I	II	III	V
HID (watt)	150	150	150	250
	250	250	250	400
Street Width, include Footpath (m)	≤ 8	≤ 10	≤ 12	≤ 15
Luminaire Spacing (m)	30	30	30	40
	40	40	40	35
Number of lanes	2	2	2	4
Arrangement (Fig. 1)	One sided	One sided	One sided	Two sided opposite
	One sided	One sided	One sided	Two sided staggered
Boom Length, *BL* (m)	1.2	1.8	2.4	1.5
Mounting height, *Mh* (m)	9.0	9.0	9.0	9.0

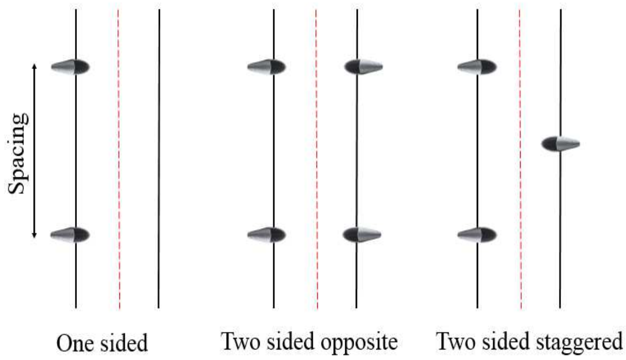

Fig.1. One sided, two sided opposite, and two sided staggeered arrangement without traffic island.

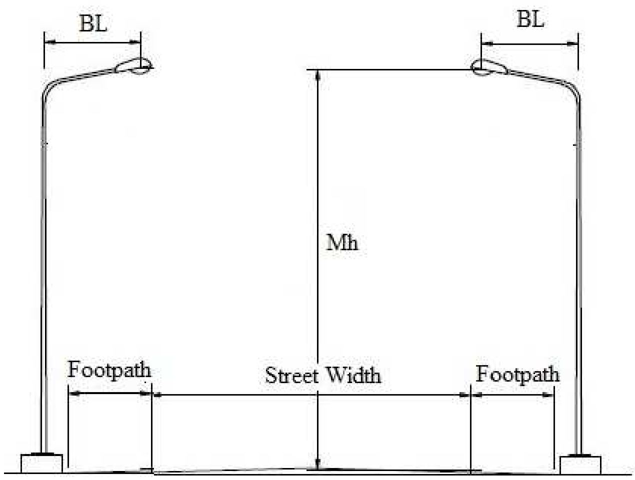

Fig. 2. shows components of street light installation including Boom Length (*BL*), Street Width and Footpath Mounting height (*Mh*).

2.3 Illuminance, luminance, and uniformity calculation

2.3.1 Illuminance calculation

The iluminance is a ratio between the lumious flux and the surface. Lux (lx) is its unit. The illuminace at point *P* (*Ep*) with *n* luminaires is calculated by Eq. (1) [11].

$$E_p = \sum_{i=1}^{n} \frac{I_{g,i}}{Mh}(\cos g_i)^3 \qquad (1)$$

where, $I_{g,i}$ is light inensity at *g* angle of *i* luminaire. *Mh* is the height between a luminaire and street.

g is the angle between *Mh* and light beam at point P.

n is the number of luminaires.

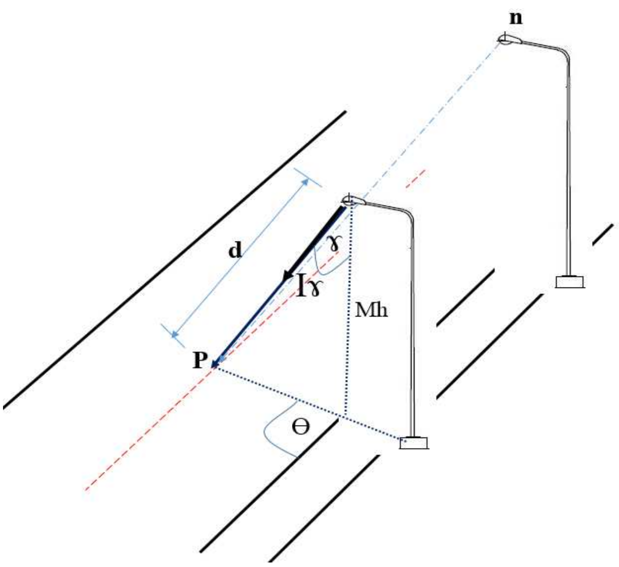

Fig.3. Street light detail

The average illuminance can be calculated by Eq. (2). $(E_p)_j$ is the illuminace at point *P* of the *j* points which base on CIE 140: 2000 standard.

$$E_{av} = \frac{\sum_{j=1}^{n} (E_p)_j}{n} \qquad (2)$$

i. Luminance calculation

The luminance (*L*) is a ratio between the luminous intensity and the area. Candela per square meter (cd/m^2) is its unit. The average luminance (L_{av}) with average illuminance relation is culculated by Eq. (3).

$$L_{av} = q \times E_{av} \qquad (3)$$

Where, *q* is the street light reflector which depends on street material.

ii. Illumination uniformity calculation

The performance of illumination uniformity (U_o) is the ratio of the minimum illumination (E_{min}) and the average illumination (E_{av}). To protect the zebra effect, the ratio of the minimum illumination (E_{min}) and the maximum illumination (E_{max}) and L_{av} are also considered.

3. BIG LENS AND SMALL LENS

3.1 Physical form of LED Lens

For large size lens of I shape, width, length, and height of lens are 5.5 cm, 9 cm, and 2.5 cm. On the other hand, width, length, and height of small size lens are 0.5 cm, 1 cm, and 0.3 cm. Lens are compacted in a luminaire shown in Fig.4.

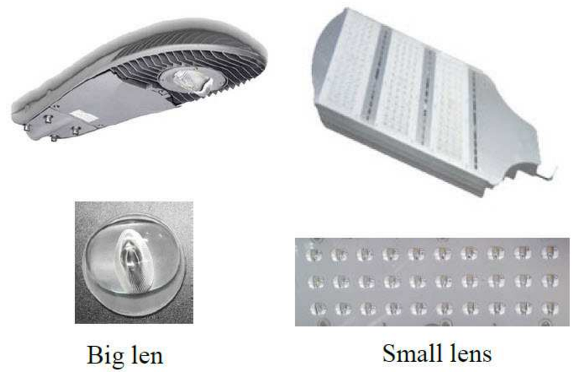

Fig. 4. LED luminaires: Big lens and small lens [12]

3.2 Polar form of light distribution

Polar form is a pattern of the light intensity (Iɤ) in some angles (ɤ) which is shown in Fig.4 and Fig.5 on C-ɤ system (C_0, C_{90}).

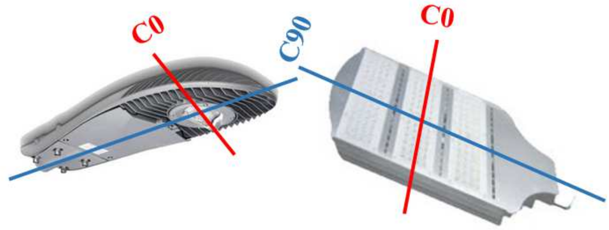

Fig.5. Luminaires of C-ɤ system

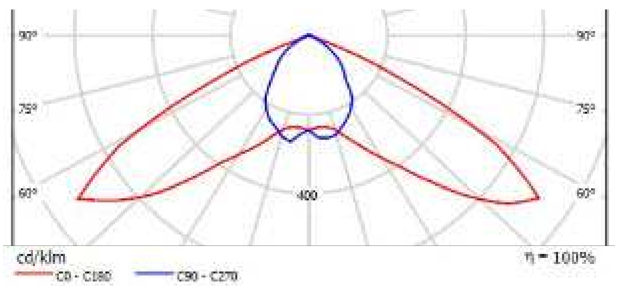

Fig. 6. Light distribution for 70 watt LED with big lens

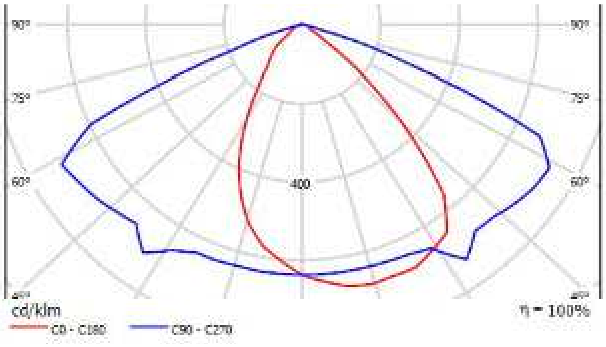

Fig. 7. Light distribution for 70 watt LED with small lens

4. EXPERIMENT AND SIMULATION RESULTS

LED with four types of big lens including O shape, I shape, oval shape, and U shape can generate different light patterns on white papers which represent street. For instance, the O shape len gives circle light on only one part of street. I shape and oval shape lens give light over street area and oval shape len give smoother than I shape len. The U shape len can give smooth rectangular light and non over light on the street shown in Fig 8. However, the U shape len is secret. In this paper, the I shape LED is ruled because it is used more than O shape, oval shape, and U shape in the present market. Moreover, the oval shape and U shape is used for only big len.

Fig. 8. Light distribution of big lens types (Type I: O shape, Type II: I shape, Type III: oval shape, Type V: U shape.

Maintenance Factor (MF) and road class are set to 0.67 and R4 (Mastic asphalt) in DIALux program.

4.1 The I shape lens with simulated isolines

Simulated isolines are light lines on the street map and made by DIALux program. The isolines present the bounary of illuminance (lux) and luminance (cd/m2) intensity. They show light distribution and uniformity on the street. The isolines shape depends on LED lens types, luminaire spacing, street types, and luminaire arrangement.

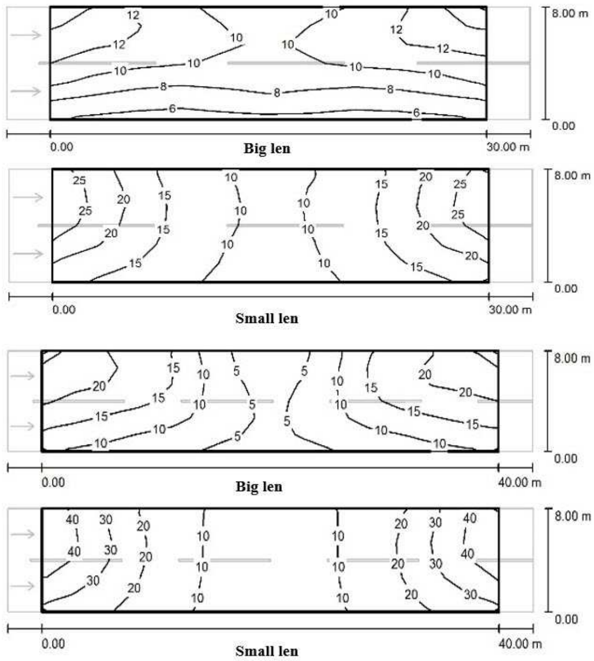

Fig. 9. Simulated isolines of illuminance (lx) for street type I (One sided arrestment).

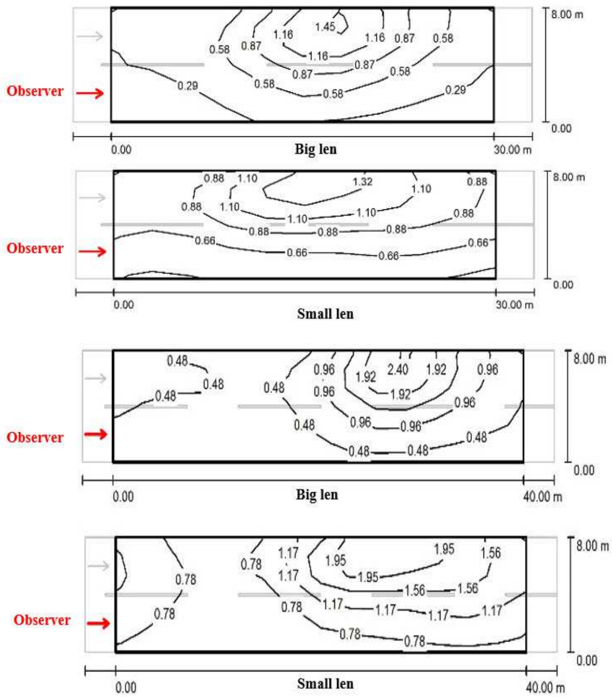

Fig.10. Simulated isolines of luminance (cd/m^2) for street type I (One sided arrestment).

The practical areas are 30 m x 8 m and 40 m x 8 m in Fig. 9 and Fig. 10. Isolines of Fig. 9, 10, 11, 12 show different intensities and several patterns of light which depend on LED watt size and luminaires locations. For illuminance isolines of Fig.9 and Fig.11, the highest intensity (lx) is at the area under the luminaire. There are two lanes with street type I – II and four lanes with street type V.

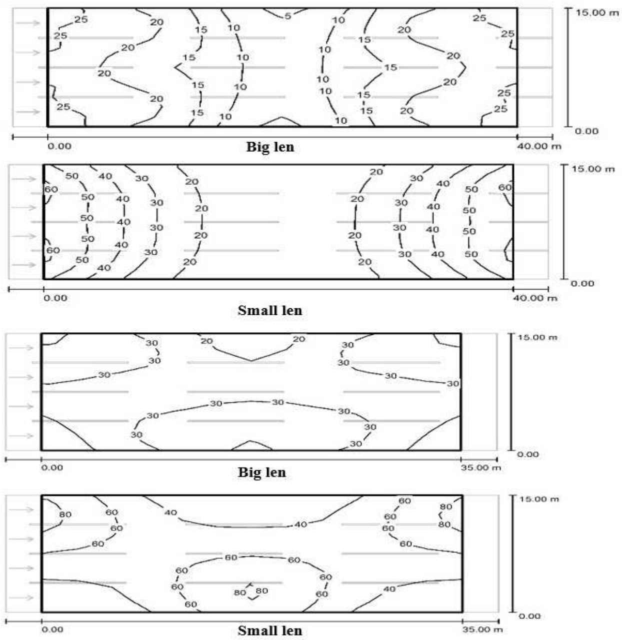

Fig.11. Simulated isolines of illuminance (lx) for street type V (Two sided opposite and staggered arrestment).

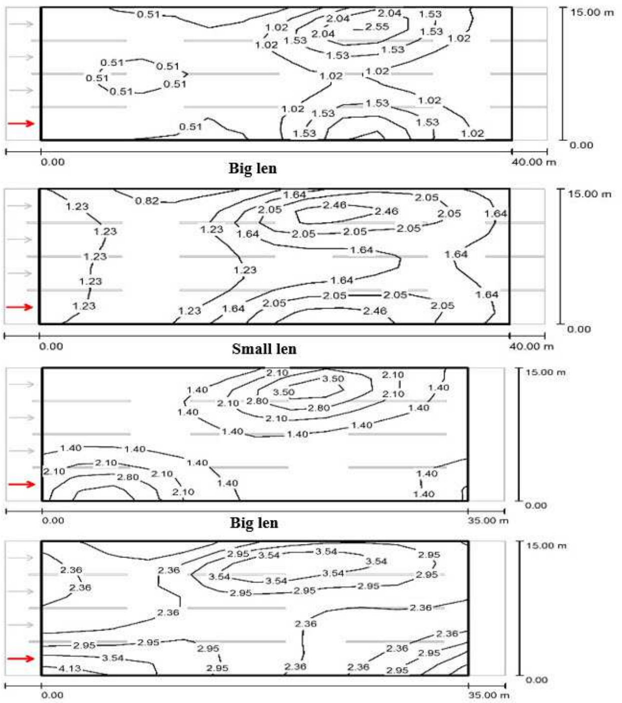

Fig.12. Simulated isolines of luminance (cd/m^2) for street type V (Two sided opposite and staggered arrestment).

Observers or drivers receive reflected light in their field of seeing view which is parallel the driving direction. The lowest average luminance of two observers with two lanes and four observers with four lanes will be compared to the luminance standard shown in Fig. 10 and Fig. 12.

The street type V areas are defined to be 40 m x 15 m of two sided opposite arrestment and 35 m x 15 m of two staggered arrestment in Fig. 11 and Fig. 12. The number of luminaires and LED watt size are more than the street types I-III. As a result, E_{av} and L_{av} of street type V are much better than street types I-III shown in Table 3 and Table 4.

4.2 The I shape lens with simulated light performance

The simulated light performance composes of illuminance, luminance, and uniformity which are calculated by DIALux program in street light standard for department of Thai highway (2011).

Table 3. The light performance results of LED Street light with big lens

Street Type	I	II	III	V
LED (watt) placement	70	70	70	120
	120	120	120	180
Illuminance, $E_{av} \geq 9.7$ lux	9.7	8.7	7.7	17
	12	11	9.96	29
Luminance, $L_{av} \geq 0.75$ cd/m^2	0.54	0.51	0.45	0.94
	0.75	0.65	0.58	1.61
Uniformity U_o, E_{min} / E_{av} ≥ 0.40	0.60	0.47	0.33	0.26
	0.21	0.25	0.26	0.48
Uniformity E_{min}/E_{max} ≥ 0.17	0.40	0.28	0.18	0.16
	0.11	0.11	0.10	0.33

Note: "_" means that the light performance is less than Thai Street Lighting Highway Standard.

In Table 3, for street type V, street width is between 12 m and 15 m, luminaire spacing 35 m, two sided staggered arrangement. The big lens with 180 watt LED can be used for street type V because luminaire spacing of LED (35 m) on street type V is less than (40 m) street types I-III, to increase E_{min} and bigger size of LED (180 watt) of street type V gives more illuminance than LED size (70 watt and 120 watt) of street types I-III.

Table 4. The light performance results of LED Street light with small lens

Street Type	I	II	III	V
LED (watt) placement	70	70	70	120
	120	120	120	180
Illuminance, $E_{av} \geq 9.7$ lux	15	14	13	31
	20	19	17	53
Luminance, $L_{av} \geq 0.75$ cd/m^2	0.76	0.80	0.75	1.57
	1.04	0.97	0.86	2.71
Uniformity U_o, E_{min} / E_{av} ≥ 0.40	0.80	0.77	0.56	0.34
	0.34	0.36	0.39	0.51
Uniformity E_{min} / E_{max} ≥ 0.17	0.31	0.30	0.28	0.20
	0.14	0.14	0.15	0.33

For comparison between Table 3 and Table 4, small lens give better light performance than big lens because beam angle (150^o) of small lens is wider than big lens (120^o) which is parallel to street. However, small lens-uniformity indices of types I-III with luminaire spacing 40 m are less a little than Thai street light standard. On the other hand, big lens are suitable to only street type V with luminaires spacing 35 m. Average illuminance and average luminance inverse street width. Moreover, light uniformity inverses luminairs spacing. However, Table 3 and Table 4 don't include lighting environment such as moon light, building light, and etc.

4.3 The I shape lens with calculated energy saving and CO_2 reduction

CO2 mission factor of Thai electricity generation increased approximately from 0.57 to 0.60 kg/kWh in 2001 to 2006 [13]. Optimal LED street light placement can reduce CO2 mission because of saving energy.

Table 5. Energy saving and CO_2 reduction after LED placement

Street Type	I	II	III	V
HID (watt / luminaire)	150	150	150	250
	250	250	250	400
LED (watt) placement	70	70	70	120
	120	120	120	180
Power reduction (watt)	80	80	80	130
	130	130	130	220
Power reduction (kWh/year)	350.4	350.4	350.4	569.4
	569.4	569.4	569.4	963.6
CO_2 reduction (kg/year)	210.2	210.2	210.2	341.6
	341.6	341.6	341.6	578.1

Note: Average CO_2 emission in Thailand is approximate to 0.6 kg/kWh [9]

For street type I, II, and II, LED Street light with 30 m and 40 m can save 80 watt and 130 watt per luminaire or 350.40 kWh and 569.40 kWh per luminaire per year. And they reduce CO_2 emission 0.21 ton and 0.341 ton per luminaire per year.

For street type V, LED Street light with spacing 40 m and 35 m can save 130 watt and 220 watt per luminaire or 569.40 kWh and 963.60 watt per luminaire per year. And they reduce CO_2 emission 0.341 ton and 0.578 ton per luminaire per year

5. CONCLUSION

In this paper, LED Street light with small lens including 70 watt, 120 watt, and 180 watt can replace 150 watt 250 watt and 400 watt HID, respectively on street type I with luminaires spacing 30 m, street type II with luminaires spacing 30 m, street type III with luminaires spacing 30 m, and street type V with luminaires spacing 35 m and 40 m. On the other hand, 180 watt LED Street light with I shape - big lens can replace only 400 watt HID on street type V with luminaires spacing 35 m. LED Street with U shape - big lens and street light with traffic island case for department of Thai highway remain to be investigated.

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