Optimization of Road Lighting Distribution of Road Luminaires for Dry and Wet Road Surface

Stanimir Stefanov, Vulchan Georgiev, Iva Draganova, Hristo Vasilev
Technical University - Sofia, Bulgaria

Abstract

The typical street lighting calculations are done for dry road surface. The reflection characteristics of the road surface change dramatically when it is wet – the mirror component of the surface reflection curve rises significantly. The desired luminance can be achieved with reduced lighting flux In such a conditions and lighting distribution of luminaires can be transformed for better lighting quality. The lighting distribution curve of classical luminaires equipped with discharge lamps is a constant and if the lamp is dimmed the intensity of light is change but its space distribution is kept. Introduction of LEDs in road lighting makes possible not only the light flux but also the lighting distribution of luminaires to be changed in real time during the exploitation of lighting system. A luminaire with two different lighting distribution curves – suitable for dry and for wet conditions is introduced in the paper. An optimal space distribution of lighting flux is searched in both cases.

Introduction

As it is well known, the LEDs are point light sources. According to the contemporary technologies, it is most efficient to use low power LEDs– 1 ÷ 5 W, that have light output in the interval 130 ÷ 180 lm/W. This is the reason why usually the street luminaires are equipped with 30 to 90 LEDs. The light distribution of the LEDs, unlike that of the conventional light sources, can be most efficiently modelled through secondary lenses, instead of reflectors. The LED luminaires can be equipped either with individual lenses for each of the LEDs or with single optical system, including all the LEDs. When individual lenses are used they can be with individual light distribution, but it is also possible to model a luminaire with changing light distribution, which can be used for different weather conditions – according to the weather different parts of the optical system will be employed with different luminous flux.

LED luminaire with manageable light distribution

If every LED is equipped with individual lens with individual light distribution and is individually dimmed by a control system, then the overall light distribution of the luminaire will be a geometrical sum of the light distributions of the separate LEDs, weighted by a factor that takes into account the level of dimming of each LED.

The individual dimming factor can be defined as:

$$k_i = \frac{E_i}{F_n}, \qquad (1)$$

Where F_n is the nominal flux of the LED and F_i is the current flux of the i^{th} LED while dimmed.

If $I_{LED\ i}$ is the light distribution of the i^{th} LED and it is presented in the "γ-C" planes, then:

$$I_{LED\,i} = \gamma \downarrow \begin{array}{c} C \rightarrow \\ \begin{bmatrix} I_{11} & I_{12} & \dots & I_{1n} \\ I_{21} & I_{22} & \dots & I_{2n} \\ \dots\dots & & & \\ I_{m1} & I_{m2} & \dots & I_{mn} \end{bmatrix} \end{array} \qquad (2)$$

And the light distribution of the LED in given direction will be:

$$I = n_1\, k_1\, I_{LED\,1} + \dots . + n_s\, k_s\, I_{LED\,s} \qquad (3)$$

Where s is the number of different individual light distributions and n_i is the number of LEDs in the luminaire, having the same light distribution.

To avoid complication of the construction of the luminaire, it is possible to divide the LEDs into groups with separate optical systems instead of individual lenses and to control them by groups in real time.

Optimal light distribution for dry and wet road surface

To investigate the possibility of creating an energy-efficient LED luminaire with adjustable light distribution for dry and wet road surface, aiming reduction of the energy consumption in rainy weather and wet road surface, an optimization task can be defined. This task can be decided regarding the luminous flux, needed to achieve the regulated levels of qualitative and quantitative indicators for street lighting.

Canonical form of the optimization task for optimal light distribution curve of a street luminaire, while minimizing its luminous flux F_{lum} is given below:

- optimization task:

$$\min(F_{lum}) \qquad (4)$$

- constraints:

$$\left| \begin{array}{l} L_{av} \geq L_{av\,rec.} \\ U_0 \geq U_{0\,rec.} \\ U_l \geq U_{l\,rec.} \\ TI \geq TI_{rec.} \\ SR \geq SR_{rec.} \\ [I(C,\gamma)] \leq [I_{constraint\,s}] \\ K_{amplf} \leq K_{set} \end{array} \right. \qquad (5)$$

The constraints are composed, based on the norm values of the quantitative and qualitative indicators for the given light situation according to EN 13201, the value of the amplification coefficient for the relevant photometric body and the constraints for the value of the light intensity in the different zones for the C and γ angles, related to the possibility of technical realization of photometric body (the difference between two adjacent intensities distant from each other at 5^o should not be more than 100 cd/klm). In the restrictions, a computational structure for regulation of the intensity values I (80^o,C) is also introduced –they should be smaller then 100 cd/klm and the values of the I(90^o,C) should tend toward 0 cd/klm.

The luminous flux of the luminaire is determined by the method of zonal flows for 5-degree spatial zones of the lower hemisphere. Only the lower hemisphere is considered, where the whole radiation of the luminaire is concentrated. It is assumed that the device is radiating symmetrically to the longitudinal plane of symmetry.

Geometric formulation of the optimization problem is shown on Figure 1. The indications on the Figures are as follows:

1 –one way roadway boundaries;
2 – luminaire, defining the beginning of the calculation field;
3 - luminaire, defining the end of the calculation field;
4 - calculation field;
5 - middle of the calculation field;
6 – observation direction;
7 – distance between the observer and the beginning of the of the calculation field.

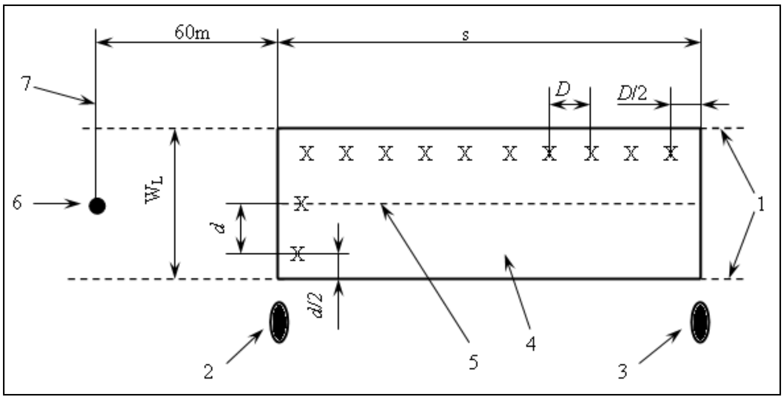

Figure 1 Geometry of the calculation field

In the longitudinal direction the distance between the calculation points is:

$$D = \frac{S}{N}, m \quad as \quad D \leq 3m \tag{6}$$

- S is the distance between two poles, m;
- N is the number of points in longitudinal direction.

In the transverse direction the longitudinal rows of the calculation points are located at a distance:

$$d = \frac{W_L}{3}, m \tag{7}$$

where W_L is the width of the relevant one way roadway, as the outer rows are situated at a distance d/2 from the end of the roadway.

For description of the light distribution curves, a function based on orthogonal polynomials of Lejandar of ninth order is used, which gives good approximation and description of the light distribution curves [1].

$$I'(C,\gamma) = \exp\begin{pmatrix} d_0(\gamma_i) + d_1(\gamma_i)\overline{C}_j + d_2(\gamma_i)\overline{C}_j^2 + d_3(\gamma_i)\overline{C}_j^3 + \\ + d_4(\gamma_i)\overline{C}_j^4 + d_5(\gamma_i)\overline{C}_j^5 + d_6(\gamma_i)\overline{C}_j^6 + d_7(\gamma_i)\overline{C}_j^7 + \end{pmatrix} \tag{8}$$

where:

- $d_p(\gamma_i)$, (p=0, 1, 2, 3, 4, 5, 6, 7) are coefficients, expressed by orthogonal polynomials of Lejandar:

$$d_p(\gamma_i) = q_{p1}S_1(T_i) + q_{p2}S_2(T_i) + ...q_{pm}S_m(T_i) \tag{9}$$

S_k is polynomial of Lejandar of k order, and T_i is an argument, changing in the range [–1; 1], calculated by:

$$T_i = \frac{2\gamma_i - \gamma_1 - \gamma_n}{\gamma_1 - \gamma_n} \tag{10}$$

γ_1 and γ_n are the first and the last value of the angle γ ;

$\overline{C}_j = \dfrac{C_j}{\max(C)}$ changes in the range [0,1].

i is the index for the number of the angle γ , and j is the index for the number of C-planes, arranged according to the table of the light distribution curve.

The q_{pk} coefficients are the unknown, searched for with the optimization algorithms. In the initial conditions of the algorithms initial matrices with q_{pk0} values are used, obtained by approximation of existing light distribution curves.

The calculations include a total number of eight luminaires – four before and four after the end of the calculation field .The results show that with the obtained light distribution curves, the major contribution for the luminance have the two closest lumiaires and partly the next two luminaires for the given pole height.

As an example, the light distribution obtained by minimization of the luminous flux for a local road – illuminance class ME4b normed by luminance is shown.

A lighting situation B2 is taken in consideration – single roadway with two lanes, main users are motorized vehicles, the typical speed 60–30km/h, slow vehicles, bicyclists and pedestrians are also permitted, and parked vehicles have to be considered.

- Illuminance class ME4b
- Traffic less than 7000 vehicles per day, without conflict zones and normal complexity of field vision
- Street coating of the roadway R3;
- Distance between two poles - s = 30m;
- Width of the roadway- b = 7m;
- Number of lanes – 2;
- Maintenance factor MF = 0,7;

  Lighting performance requirements:
- Average luminance $L_{av\ rec.}$= 0,75 cd/m2;
- Minimal value of U_l = 0,5;
- Minimal value of U_0 = 0,4;
- Maximal value of TI = 15;
- SR = 0,5;
- Single row luminaires, with distance pole to roadway 0m. The presented distribution of the luminance is for the observer, for whom the value of the average luminance is the lowest.

On Figures 2 and 3 the optimal light distribution curves for dry and wet surfaces are shown. The following results are obtained with the curves:

<u>Dry roadway</u>
Mounting height – H = 8m;
L_{av} = 0,75 cd/m^2;
U_l = 0,5;
U_0 = 0,4;
TI = 15;
SR = 0,5;
F_{source} = 5456 lm.
K_{ampff} = 7

<u>Wet roadway</u>
Mounting height – H = 8m;
L_{av} = 0,75 cd/m^2;
U_l = 0,61;
U_0 = 0,15;
TI = 4,74;
SR = 0,58;
F_{source} = 2845 lm
K_{ampff} = 7

Real time control of the light distribution

A LED street luminaire with 35 LEDs with single power of 3 W and light output of 70 lm/W is considered.

DRY STREET COATING AND LED LUMINAIRE
Mounting height – H = 8m;
L_{av} = 0,75 cd/m^2;
U_l = 0,54; luminary
U_0 = 0,41;
TI = 12.3;
SR = 0,51;
F_{source} = 6800 lm

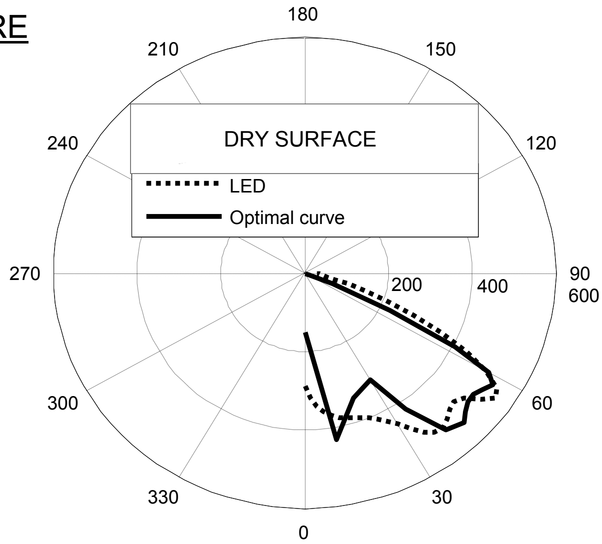

Figure 2 Optimal light distribution curve for C15° plane and light distribution for the same plane, achieved by dimming of the LEDs in the luminaire. The results are for dry and wet street coating. The curve is given for 1000 lm.

Two of the LEDs are mounted in flareBXP lens, [2], eight with stradaAXP lens, [3], and twenty five with stradaB2XP lens, [4]. The lenses are mounted in the luminaire on a plane tilted 5 to the horizon.

When the road surface is dry, all the LEDs are on and they emit 100% of their luminous flux, except the eight with stradaAXP lens, which are dimmed to 80% of their nominal luminous flux. The light distribution curve, obtained for this situation is shown on Figure 2. The luminous flux of the luminaire is 6800 lm, and the lighting requirements met are:

WET STREET COATING AND LED LUMINAIRE
Mounting height – H = 8m;
L_{av} = 0,76 cd/m^2;
U_l = 0,59;
U_0 = 0,42;
TI = 7.2;
SR = 0,54;
F_{source} = 3570 lm

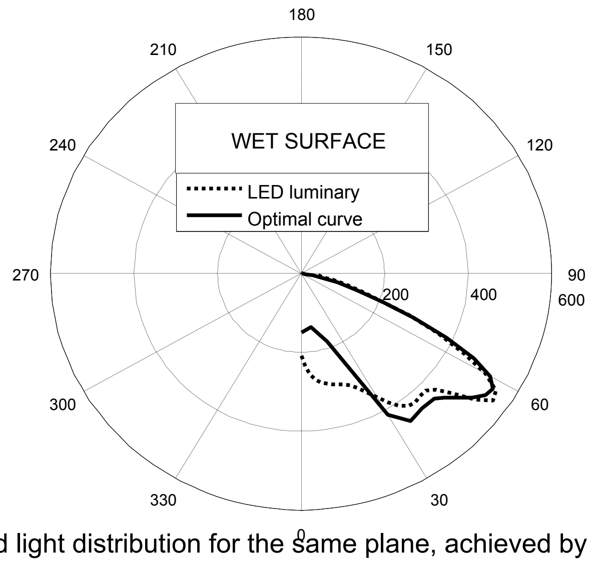

Figure 3 Optimal light distribution curve for C15° plane and light distribution for the same plane, achieved by dimming of the LEDs in the luminaire. The results are for wet street coating. The curve is given for 1000 lm.

Using these principles, additional energy savings can be achieved, as well as improvement of the quality of the lighting. The drawback of such a luminaire is the great number of LEDs with low light output needed. When using small number of LEDs with greater light output for more precise control of the light distribution, it is necessary to use light distribution curves for which the main difference in the form of the light distribution to be fulfilled only with dimming of the luminous flux value, instead of changing the curves form as a whole. This idea can be realized with the use of luminaires with great amplification coefficient, because their luminous flux is usually concentrated in a narrower zone (Figure 6 and Figure 7) for example when K_{amplf} = 7 (Figure 4 and 5 – Figure 4, 5, 6 and 7 theoretical optimal curves, obtained for luminous flux of 1000 lm [6], [7]).

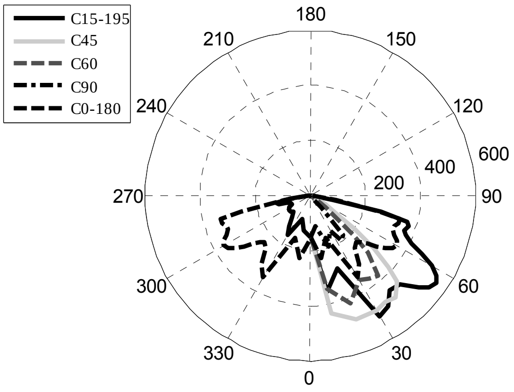

Figure 4. Light distribution curves:
dry surface - L_{av} = 0,5cd/m^2; s = 32m;
F_{lum} = 3210 lm; K_y = 7

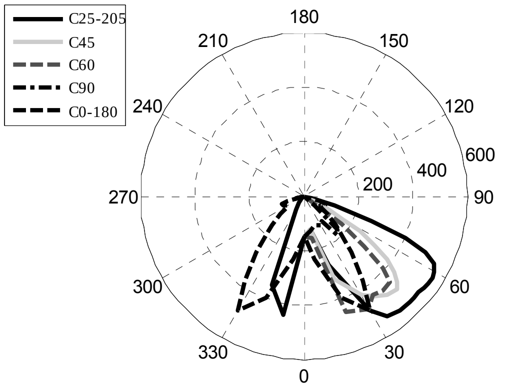

Figure 5. Light distribution curves:
Wet surface - L_{av} = 0,5cd/m^2; s = 32m;
Flum = 2614 lm; Ky = 7

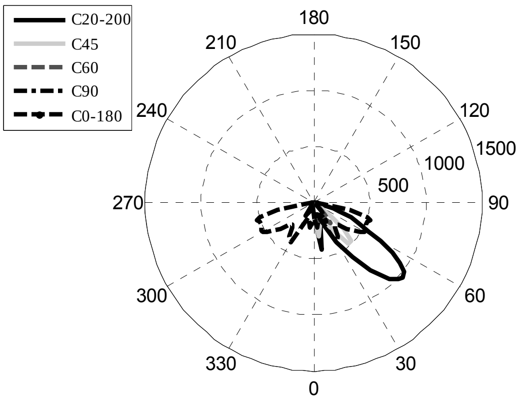

Figure 6. Light distribution curves:
dry surface - Lav = 0,5cd/m2; s = 32m;
Flum = 2352 lm; Ky = 13

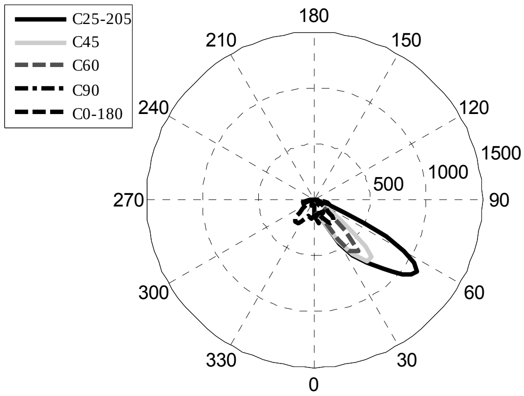

Figure 7. Light distribution curves:
wet surface - Lav = 0,5cd/m2; s = 32m;
Flum = 1370 lm; Ky = 14

Figure 8. Dry surface

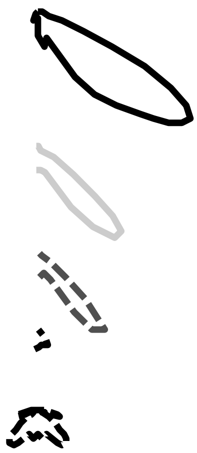

Figure 9. Wet surface

Figure 10. Dry and Wet surface

As shown on Figure 10, there is significant overlap of the curves in the direction of maximum intensity, as the difference of the angles for the γ and C – planes is 5 degrees. In this direction there will be significant approximation of the shape of the curves and proportionality of the intensity values. The main difference appears in the intervals $0^o \div 15^o$ and $50^o \div 85^o$ for the C – planes of the light distribution curves shown. The main advantage of the light distribution with higher values of the gain coefficient is the substantially smaller luminous flux, required to reach luminance levels needed, compared to those reached with a gain coefficient of 7.

Conclusions

The creation of a luminaire, giving the opportunity to meet the lighting requirements both for dry and wet road surface is a complicated task that can be decided on the base of significant informational resource and previous theoretical knowledge. The appropriate choice of lenses and individual control of the LEDs allows real time control of the light distribution of the luminaires. This leads simultaneously to increased quality of the street lighting when the road surface is wet, and the decrease of the maintenance expenses.

According to [5], the average number of the rainy days in Bulgaria is 66. The luminous flux needed for illumination of wet surface is twice smaller than that for dry surface, which means that the control method, proposed in the current paper can decrease the expenses for electrical energy with nearly 10%.

This is achieved through more complicated control system – both for the drivers, feeding the LEDs in the luminaires and the control system of the lighting installation of a settlement. The electronic industry evolve in a fast rate, so with time it is expected that the price of the LEDs and the lenses needed for the luminaire proposed will decrease and they will become economically profitable in near future.

References

[1] Velinov K., Hr. Vasilev. " Influence of geometrical parameters and regulatory restrictions on the optimal light distribution of street luminaires, Illumination 2007. XIII National Conference, Varna, Bulgaria, 2007, pp. 94-104..
[2] Ledil F'form Optics, Flare-B-XP lens for Cree XP-E/C series of LEDs, www.ledil.com.
[3] Ledil F'form Optics, STRADA-A-XP LENSES FOR CREE XP-E LEDs, www.ledil.com.
[4] Ledil F'form Optics, STRADA-B2-XP LENSES FOR CREE XP-E LEDs, www.ledil.com.
[5] Climate Guide of Bulgaria
[6] Stefanov St., Research on the influence of factor of amplification of street luminaries when minimizing their lighting flux for street designed by STV method, Journal of the Technical University Sofia, branch Plovdiv "Fundamental Sciences and Applications", Vol. 16, 2011, pp. 353-358. ISSN 1310-8271
[7] Stefanov St., Research on the influence of factor of amplification of street luminaries when minimizing their lighting flux for wet street designed by STV method, Journal of the Technical University Sofia, branch Plovdiv,"Fundamental Sciences and Applications", Vol. 16, 2011, pp. 359-364. ISSN 1310-8271

Acknowledgement

The results, published in this paper, are related to the topic and investigated for scientific project DUNK 03/1.

Authors

Stanimir Blagoev Stefanov, Assistant Professor, PhD, TU - Sofia, Plovdiv Branch, e-mail: glasst@abv.bg
Vulchan Todorov Georgiev, Associated Professor, TU - Sofia, e-mail: vulchy@tu-sofia.bg
Iva Dimitrova Draganova, PhD student, TU - Sofia, e-mail: iva_draganova1986@abv.bg
Hristo Nikolov Vasilev, Professor, TU - Sofia, e-mail: hristo.vasilev@denima2001.com