Design of LED freeform optical system for road lighting with high luminance/illuminance ratio

Zexin Feng,[1] Yi Luo,[1,2,*] and Yanjun Han[1]

[1]*State Key Lab on Integrated Optoelectronics/Tsinghua National Lab on Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing, 10008 China*
[2]*Semiconductor Lighting laboratory, Graduate School at Shenzhen of Tsinghua University, Shenzhen, 518055 China*
**luoy@tsinghua.edu.cn*

Abstract: A systematic method is proposed for designing an optical system for road lighting using an LED and a freeform lens that is optimized to produce a certain luminance distribution on the road surface. The proposed design method takes account of the luminance characteristics of the road surface, the energy efficiency of the system, the glare problem of the luminaire and the effects of four adjacent luminaries illuminating a single road surface. Firstly, the road surface illuminance with a polynomial of cosine functions along the road is optimized to maximize Q (the ratio of the average luminance to the average illuminance) as well as satisfying the lighting requirements provided by CIE. Then, a smooth freeform lens with this optimized illuminance is designed based on the variable separation method and the feedback modification method. Results show that, from two typical observer positions on the 2-lane C2 class road, luminaires with these freeform lenses can provide Q values of 7.90×10^{-2} and 8.69×10^{-2}, the overall road surface luminance uniformity of 0.55 and 0.56, the longitudinal road surface luminance uniformity of 0.72 and 0.79, and the glare factors of 10.06% and 6.73% .

©2010 Optical Society of America

OCIS codes: (080.4298) Nonimaging optics; (220.2945) Illumination design; (230.3670) Light-emitting diodes.

References and links

1. Kim lighting luminaire product catalogs. "WARP 9 LED", (Kim Lighting, 2009), *http://www.kimlighting.com/*
2. Y. Luo, Z. Feng, Y. Han, and H. Li, "Design of compact and smooth free-form optical system with uniform illuminance for LED source," Opt. Express **18**(9), 9055–9063 (2010), http://www.opticsinfobase.org/abstract.cfm?URI=oe-18-9-9055.
3. CIE, (commission Internationale del'Eclairage). Calculation and Measurement of luminance and illuminance in Road Lighting (CIE publication 30.2, Vienna, 1982).
4. CIE, (commission Internationale del'Eclairage). Road surfaces and lighting (CIE publication 66, Paris, 1984).
5. A. Pachamanov, and D. Pachamanova, "Optimization of the light distribution of luminaires for tunnel and street lighting," Eng. Optim. **40**(1), 47–65 (2008).
6. L. Wang, K. Y. Qian, and Y. Luo, "Discontinuous free-form lens design for prescribed irradiance," Appl. Opt. **46**(18), 3716–3723 (2007).
7. CIE, (commission Internationale del'Eclairage). Glare and uniformity in road lighting installations. (CIE publication 31, Paris, 1976).
8. Y. Han, X. Zhang, Z. Feng, K. Qian, H. Li, Y. Luo, X. Li, G. Huang, and B. Zhu, "Variable-separation three dimensional freeform nonimaging optical system design based on target-to-source mapping and micro belt surface construction, " Sciencepaper Online 1–9(2010). *http://www.paper.edu.cn/en/paper.php?serial_number=201002-443*
9. CIE, (commission Internationale del'Eclairage). Recommendations for the lighting of roads for motor and pedestrian traffic, (CIE publication 115, Vienna, 1995).
10. Cree LED products. "XLamp Xp_G LEDs datasheet", (CREE, 2010), *http://www.cree.com/products/xlamp_xpg.asp*

#133129 - $15.00 USD Received 9 Aug 2010; revised 18 Sep 2010; accepted 22 Sep 2010; published 1 Oct 2010

1. Introduction

The ultimate purpose of road lighting is to facilitate safe and comfortable night-time driving. HPS (High pressure sodium) luminaires have been widely used for road lighting because of their high efficacy. However, it's impossible to control all the light rays emitted from a large size HPS source within the effective region, resulting in light pollution and energy waste. Furthermore, its poor color rendering has negative influence on the driver's ability to differentiate objects on the road.

Compared with traditional light sources, Light emitting diodes (LEDs) have differed themselves by high efficacy, small size, better color rendering, long life and environmental friendliness, etc. However, because of their Lambertian radiation distribution, LEDs usually can't be directly used for road lighting. Hence, luminaires with different directional LEDs and reflectors are designed to achieve desired illumination patterns [1]. However, their complex structures result in decreased reliability and increased difficulty in LED installation. Usage of the freeform optical systems can avoid this problem, where light rays emitted from the LED sources mounted at a flat installation board are usually refracted to achieve a desired illuminance distribution [2].

However, current design methods of the freeform optical systems for road lighting focus on achieving a uniform rectangular illuminance distribution [2], while the road surface luminance (also depending on the observer's position and the road surface's reflection properties) is ignored. The standard observer's position was defined by CIE [3], and the reflection properties of the road surfaces are usually described by the reduced luminance coefficient $r(\beta,\gamma)$, wherein β is the angle between the light incident plane and the observation plane, and γ is the angle between the light ray and the vertical axis of the luminaire. Then, the road surface luminance $L(\beta,\gamma)$ can be obtained as Eq. (1) [3]:

$$L(\beta,\gamma)=\sum_{k=1}^{K}\frac{r(\beta,\gamma)}{10^4\cdot\cos^3\gamma}\cdot E_k(c,\gamma) \tag{1}$$

wherein $E_k(c,\gamma)$ is the illuminance produced by the (k)-*th* luminaire, $k = 1,2,3,\ldots K$, and c is the angle between the projection line of the light ray on the road and the road axis. The variables of luminance calculation are illustrated in Fig. 1. Values of $r(\beta,\gamma)$ were provided by CIE in the 1970s with tables for four typical road surfaces (R1, R2, R3, and R4) . In 1984, a new classification system using only two classes (C1 and C2 for concrete and asphaltum road surfaces, respectively) has also been introduced by CIE [4].

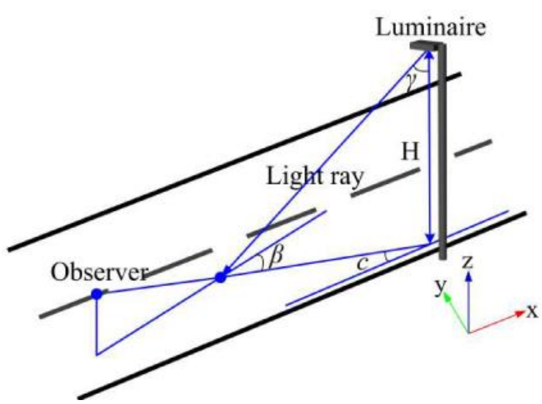

Fig. 1. Illustration of the variables of luminance calculation.

As shown in Fig. 2, two adjacent luminaires with uniform illuminance can produce strong brightness contrast on the C2 road surface between them. This will result in 'Zebra effect' (repeated bright and dark regions) on the whole road surface, which may cause strong psychological and visual disturbance to drivers. Hence, road lighting design should take the road surface luminance into account, which significantly increased the design complexity. First, compromise should be made between the luminance uniformity and energy efficiency: maximum luminance uniformity may reduce the average luminance and make the road lighting design less energy efficient [5]. Second, trade-off between the average luminance and the glare problem should also be made: unlimited increase in the average luminance can also cause serious glare problem. In addition, at least three luminaires (two luminaires in front of and one luminaire behind the calculation region) should be considered in the luminance calculation, while only two luminaires are considered when design for the uniform illuminance.

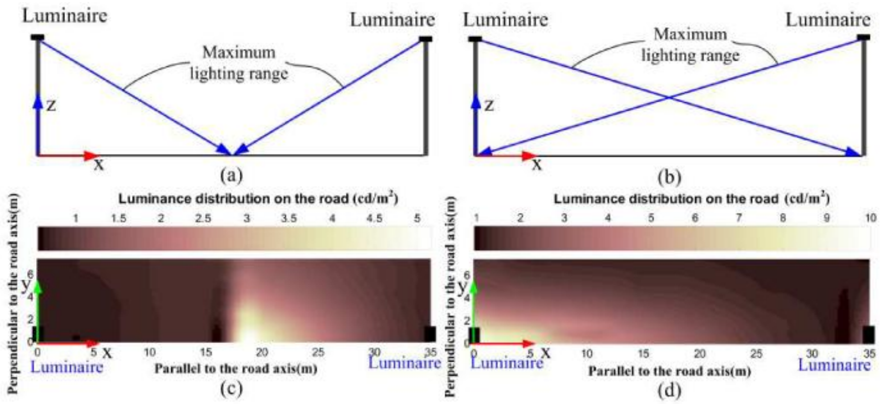

Fig. 2. Luminance distributions produced by luminaires with uniform illuminance. The mounting space S = 35m, mounting height H = 10m, road width W = 7.5m, and the observer position is (–60m, 1.875m, 1.5m). The maximum lighting range along the road of each luminaire is (a) 17.5m or (b) 35m, and the luminance distributions produced by luminaires with these two uniform illuminance distributions are shown in (c) and (d), respectively.

An optimization method based on the polynomial representation for the light intensity was proposed [5]. However, only two luminaires are taken into account in this method, and the complex polynomial light intensities with 15 coefficients may make it hard to design the smooth freeform optical system.

In this paper, we proposed a systematic method for designing an optical system for road lighting using an LED and a freeform lens, where the luminance characteristics of the road surface, the energy efficiency of the system, the glare problem of the luminaire and the effects of four adjacent luminaries illuminating a single road surface are taken into account. A polynomial of cosine functions $a_i cos^{n_i}(\pi x/2x_{max})$ for illuminance distribution is introduced, wherein x represents the coordinate along the road axis, and x_{max} is the maximum value of x. Then, the luminance distribution can be derived from Eq. (1). The problem is transformed to find the values of a_i and n_i which can maximize Q (the ratio of the average luminance to the average illuminance) as well as fulfilling the lighting requirements provided by CIE. We first design the compact optical system with this optimized illuminance distribution based on the variable separation method [6], the simulation results may have large deviations from the given illuminance distribution because of the extended light source and the freeform surface errors. By employing the feedback modification method [2], the simulation results of the freeform optical system after several iterations may approach the desired illuminance distribution. Lighting parameters calculated from the final simulation results show that we can obtain an energy efficient freeform optical system with sufficient improvement on the lighting effect.

2. Design of LED freeform optical system for road lighting

The systematic design method can be described by a flow diagram as shown in Fig. 3. The design process can be divided into two parts: illuminance optimization and design of the freeform optical system. There are generally four steps in illuminance optimization: determination of the geometrical parameters (mounting space, mounting angle, etc.), the road surface reflectance, given illuminance distribution, calculation of the lighting parameters and determining if this illuminance distribution can make the road lighting more energy efficient as well as fulfilling the lighting requirements. After optimization of the illuminance distribution, a freeform optical system can be constructed with this distribution after several iterations as follows: calculating the freeform optical model, system simulation and feedback [2].

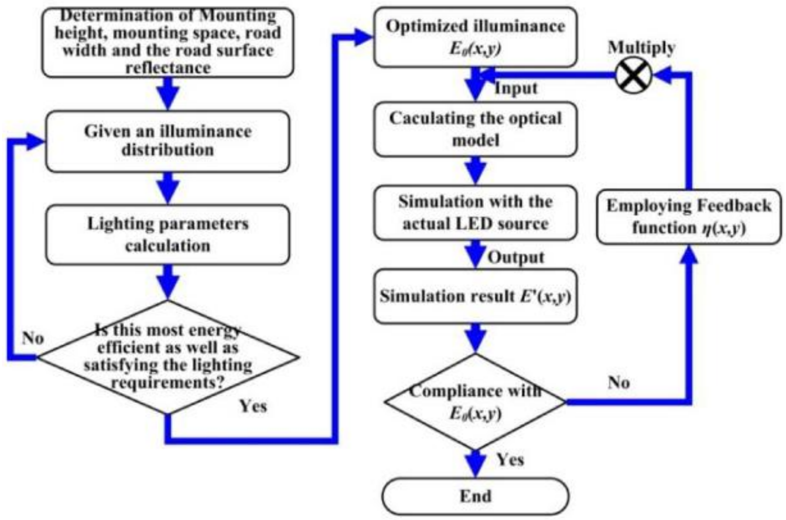

Fig. 3. Flow diagram of designing LED freeform optical system for road lighting

2.1 Illuminance optimization

As shown in Fig. 4, the road surface between two adjacent luminaires is usually set as the calculation region, and its edge line perpendicular to the road axis and passing through luminaire1 is 60m in front of the observer [3]. The calculation region is equidistantly separated into $N \times M$ rectangular cells, and coordinates (x_i,y_j) are used, wherein x, y denote the coordinates parallel and perpendicular to the road axis, respectively, $i = 1,2,\ldots,N$, $j = 1,2,\ldots M$.

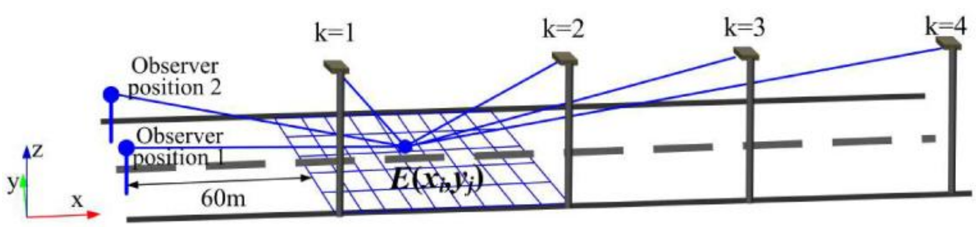

Fig. 4. Illustration of the calculation region.

Once the mounting height, the mounting space, the road width and the observer position are fixed, angles c, γ, β and the reduced luminance coefficients r can be expressed as the functions of x and y. The luminance $L(x_i,y_j)$ at the (i, j) unit cell can be written as Eq. (2):

Received 9 Aug 2010; revised 18 Sep 2010; accepted 22 Sep 2010; published 1 Oct 2010

$$L(x_i, y_j) = \sum_{k=1}^{K} \frac{r_k(x_i, y_j)}{10^4 \cdot \cos^3 \gamma_k(x_i, y_j)} \cdot E_k(x_i, y_j) \quad (2)$$

wherein $E_k(x_i,y_j)$ is the illuminance on (x_i,y_j) unit cell produced by the (k)-*th* luminaire, $k = 1,2,3,...K$. Then, road lighting can be normally specified by the following lighting parameters.

The average illuminance E_{av} and the average road surface luminance L_{av} can be obtained from Eq. (3) and Eq. (4), respectively [3]:

$$E_{av} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M} E(x_i, y_j)}{NM}, E(x_i, y_j) = \sum_{k=1}^{K} E_k(x_i, y_j) \quad (3)$$

$$L_{av} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M} L(x_i, y_j)}{NM} \quad (4)$$

The illuminance uniformity E_0 and the overall road surface luminance uniformity U_0 are defined as Eq. (5) and Eq. (6) [3]:

$$E_0 = \frac{\min(E(x_i, y_j))}{E_{av}}, i = 1, 2, ...N, j = 1, 2, 3, ...M \quad (5)$$

$$U_0 = \frac{\min(L(x_i, y_j))}{L_{av}}, i = 1, 2, ...N, j = 1, 2, 3, ...M \quad (6)$$

wherein $\min(E(x_i,y_j))$ and $\min(L(x_i,y_j))$ are the minimum values of the illuminance and the road surface luminance on the calculation region, respectively.

The longitudinal road surface luminance uniformity U_L, which is used to describe the severity of 'Zebra effect', is defined as Eq. (7) [3]:

$$U_L = \frac{\min(L(x_i, y_{center}))}{\max(L(x_i, y_{center}))}, i = 1, 2, 3, ...N \quad (7)$$

wherein $\min(L(x_i,y_{center}))$ and $\max(L(x_i,y_{center}))$ are the minimum and maximum luminance values on the central lane line passing through the observer position, respectively.

The glare factor TI (threshold increment), which is used to control the glare's interference on the drivers to perceive objects, is a function of the equivalent veiling luminance L_v and the average road surface luminance L_{av}. L_v can be computed as Eq. (8) [7]:

$$L_v = 10 \cdot \sum_{k=1}^{K} \frac{E_{ek}}{\theta_{ek}^{\ 2}} \quad (8)$$

wherein E_{ek} is the illuminance produced by the (k)-th luminaire on the observer's eyes in the plane perpendicular to the observer's line of sight, which is parallel to the road axis and directed 1° downward from the horizontal; and θ_{ek} is the angle the line passing through the (k)-*th* luminaire and observer's eyes makes with the observer's line of sight. *TI* is defined as Eq. (9) [7]:

$$TI = 65 \frac{L_v}{L_{av}^{0.8}} \quad (9)$$

for $0.5\text{cd/m}^2 \le L_{av} \le 5\text{cd/m}^2$.

The calculation of all lighting parameters above is based on the given of luminaire's illuminance distribution, where a polynomial of cosine functions is introduced as Eq. (10):

#133129 - $15.00 USD Received 9 Aug 2010; revised 18 Sep 2010; accepted 22 Sep 2010; published 1 Oct 2010
(C) 2010 OSA

$$\begin{aligned} E_0(x,y) &= E_x(x)\cdot E_y(y) \\ &= \left(\sum_{i=1}^{J} a_i \cos^{n_i}(\frac{\pi x}{2x_{\max}})\right)\cdot 1 \\ &= \sum_{i=1}^{J} a_i \cos^{n_i}(\frac{\pi x}{2x_{\max}}) \end{aligned} \tag{10}$$

wherein J is the number of coefficients a_i or powers n_i. There are several reasons for choosing this representation. First, the smoothly decreasing distribution of cosine functions can easily balance all the lighting parameters, guarantee better tolerances and obtain smooth light distribution curves. Second, it is possible to design a smooth optical system by employing the variable separation method because $E_0(x,y)$ can be separated as $E_x(x)\cdot E_y(y)$. Third, the number of variables a_i and n_i can be sufficiently small, which can speed up the optimization process. The overall road surface luminance uniformity can be sufficiently improved by optimizing $E_y(y)$, but this may also reduce Q values (the average road surface luminance to the average road surface illuminance), which is the characterization of the energy efficiency. Note that the optimization of $E_x(x)$ can always satisfy the lighting requirements, there is no need to optimize $E_y(y)$ which also results in increased complexity and time consuming of the optimization process.

Since all the lighting parameters are related to the illuminance distribution, they can be expressed as the functions of the coefficients a_i and the powers n_i. Then, the general formulations of the optimization problem can be presented as Eq. (11), Eq. (12), Eq. (13), Eq. (14) and Eq. (15):

$$\max(Q(a_1,a_2,...,a_J,n_1,n_2,...n_J)) = \max(\frac{L_{av}(a_1,a_2,...,a_J,n_1,n_2,...n_J)}{E_{av}(a_1,a_2,...,a_J,n_1,n_2,...n_J)}) \tag{11}$$

$$L_{av}(a_1,a_2,...,a_J,n_1,n_2,...n_J) \geq L_{avT} \tag{12}$$

$$U_0(a_1,a_2,...,a_J,n_1,n_2,...n_J) \geq U_{0T} \tag{13}$$

$$U_L(a_1,a_2,...,a_J,n_1,n_2,...n_J) \geq U_{LT} \tag{14}$$

$$TI(a_1,a_2,...,a_J,n_1,n_2,...n_J) \leq TI_T \tag{15}$$

wherein L_{avT},U_{0T},U_{LT} and TI_T are standard values provided by CIE.

2.2 Design of the freeform optical system

Energy conservation between the LED source and the target plane can be expressed as Eq. (16) [6]:

$$\iint_{\Omega} I_0 \cos^2 u \cos v du dv = \iint_{D} E_0(x,y) dx dy \tag{16}$$

wherein u is the angle between the light ray and x axis, v is the angle the plane that contains axis x and light ray makes with axis z which is parallel to the road lighting rods, and I_0 is the central light intensity of the LED source.

It is more difficult to solve the above integral equation because of the illuminance distribution with a polynomial of cosine functions. Based on the equidistantly separation of the target plane into sufficiently $n \times m$ rectangular cells [8], wherein $n \geq N$, $m \geq M$, the solution to the integral equation can be transformed to solve the sum equation here. Then, the polar coordinates (u,v) can be obtained from the rectangular coordinates (x,y) expressed as Eq. (17) and Eq. (18):

#133129 - $15.00 USD Received 9 Aug 2010; revised 18 Sep 2010; accepted 22 Sep 2010; published 1 Oct 2010
(C) 2010 OSA

$$u_{j+1} = f(\sum_{i=1}^{n}\sum_{j=1}^{j} E_0(x_i, y_j)) \quad (17)$$

$$v_{i+1} = g(\sum_{j=1}^{m}\sum_{i=1}^{i} E_0(x_i, y_j)) \quad (18)$$

wherein $u_1 = -\pi/2$, $v_1 = 0$, and i = 1,2,…n, j = 1,…m.

Since all the polar coordinates (u,v) are derived from Eq. (17) and Eq. (18) with the desired illuminance distribution $E_0(x,y)$, the optical model can be constructed based on the method mentioned in Refs. (2) and (6). The simulation result $E'(x,y)$ may have a large deviation from the optimized illuminance $E_0(x,y)$ because of the extended light source and the freeform surface errors.

By employing the feedback modification method, the given illuminance distribution $E_0(x,y)$ is modified through the feedback function $\eta_l(x_i,y_j) = \eta_l(E'_l(x_i,y_j), E'_{l-1}(x_i,y_j),…, E'_1(x_i,y_j), E_0(x_i,y_j))$, wherein $E'_l(x_i,y_j)$ is the simulation result of the *l-th* iteration [2]. A new feedback function is also introduced as Eq. (19) and Eq. (20):

$$\eta_l(x_i, y_j) = \beta_l(x_i, y_j) \cdot \beta_{l-1}(x_i, y_j) \cdots \beta_1(x_i, y_j) \quad (19)$$

$$\beta_l(x_i, y_j) = \frac{E_0(x_i, y_j)}{(1-\lambda)E_0(x_i, y_j) + \lambda E'_l(x_i, y_j)} \quad (20)$$

wherein $0< \lambda \le 1$, and $E_0(x_i,y_j) \neq 0$, $E'_l(x_i,y_j) \neq 0$, l = 1,2,3,….

The new given illuminance distribution can be obtained as Eq. (21):

$$E_{l+1}(x_i, y_j) = \eta_l(x_i, y_j) \cdot E_0(x_i, y_j) \quad (21)$$

The simulation result of the new optical model designed with $E_{l+1}(x,y)$ will gradually approach the optimized illuminance distribution $E_0(x,y)$ as l increases.

3. Design example

3.1 Optimization results

Supposing the mounting height, the mounting space and the road width are 10m, 35m and 7.5m (two lanes), respectively. The optimization results are obtained by setting J = 3, K = 4, x_{max} = 120m, and by satisfying the lighting category M2 recommended by CIE [9], wherein L_{avT} = 1.5cd/m^2, $U_{0T} = 0.4$, U_{LT} = 0.7 and TI_T = 10%. The calculation region is equidistantly separated into 20 × 10 cells. To be more intuitive, light distribution curves derived from the optimized illuminance distribution are shown in Fig. 5.

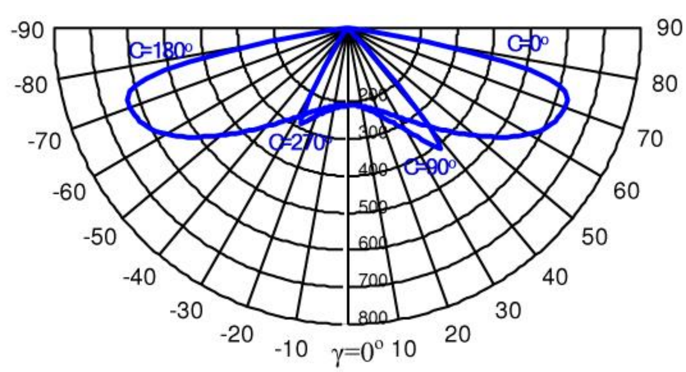

Fig. 5. Light distribution curves derived from the optimized illuminance distribution. The flux is unified into 1000lm

#133129 - $15.00 USD Received 9 Aug 2010; revised 18 Sep 2010; accepted 22 Sep 2010; published 1 Oct 2010
(C) 2010 OSA

Table 1 shows the lighting parameters calculated from the optimized illuminance distribution on the most popular C2 roads, where the average luminance values are unified into 1.5cd/m^2. All of them are within the lighting requirements of the M2 category.

Table 1. Lighting parameters calculated from the optimized illuminance

Observer position	L_{av}(cd/m^2)	U_0	U_L	TI(%)	E_{av}(lx)	E_0	Q
(−60.000, 1.875,1.500)	1.50	0.56	0.70	9.98	18.60	0.78	8.07×10^{-2}
(−60.000, 5.625,1.500)	1.50	0.55	0.78	6.99	16.96	0.78	8.85×10^{-2}

Figure 6 show the comparison of lighting parameters provided by luminaires1 (with a uniform illuminance, x_{max} = 17.5m), luminaires2 (with the optimized illuminance, x_{max} = 120m) and luminaires3 (with a uniform illuminance, x_{max} = 35m). It can be seen that U_L values produced by luminaires2 have been significantly improved compared with those produced by luminaires1 and luminaires3; luminaires2 also provide higher Q values than Luminaires1 because of their larger maximum light intensity angles (72° to 60°); although luminaires3 with highest maximum light intensity angles (about 74°) can provide most energy efficient (highest Q values) illumination, their *TI* values are far beyond acceptable ranges.

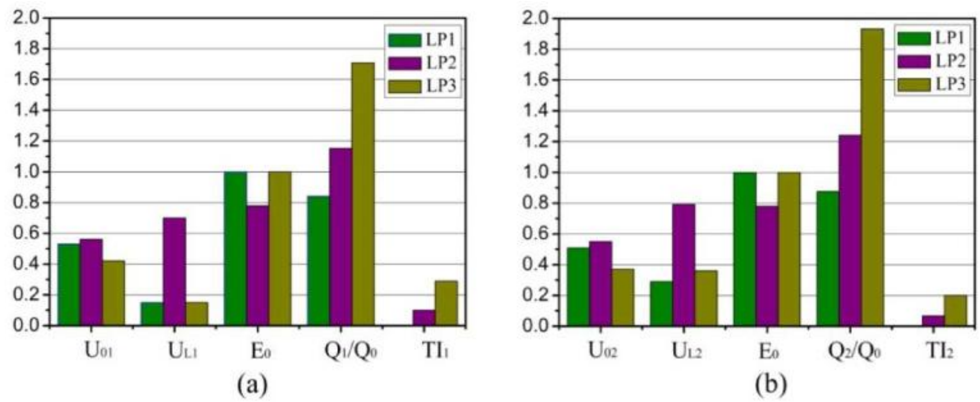

Fig. 6. Comparison of lighting parameters produced by luminaires1 (LP1), lumiaires2 (LP2), and luminaires3 (LP3) with the observer's position at (a) (−60m, 1.875m, 1.5m) and (b) (−60m, 5.625m, 1.5m). Q_0 (0.07) is the average luminance coefficient for C2 road

3.2 Lighting parameters calculated from the simulation results before and after feedback

In this section, CREE's XLamp XP-G LED is taken as the simulation light source [10]. The light distribution of 1mm × 1mm LED source can be considered as Lambertian type with full half space directional range. The lens material used is polycarbonate with the refractive index of 1.59. Since the distance from the luminaire to the road surface is much larger than the size of the luminaire, far-field approximation is adopted to simplify the simulation. Assuming there is one LED and one lens for each luminaire, the total flux can be scaled up to meet the lighting requirements. The virtual point light source used in the calculation of lens model has the same radiation distribution with the LED source.

Figure 7(a) shows the original lens model designed with the optimized illuminance distribution, and it's dimension (central length, central width and central height) is 16.48mm × 8.04mm × 6.49mm. As shown in Fig. 7(b), the light distribution curves derived from the simulation results have a large deviation from those derived from the optimized illuminance distribution, which is mainly caused by the extended light source and freeform surface errors and partially caused by the color dispersion of the polycarbonate lens; and the maximum light intensity angle declines about 10°, which may result in the reduction of Q values.

#133129 - $15.00 USD Received 9 Aug 2010; revised 18 Sep 2010; accepted 22 Sep 2010; published 1 Oct 2010
(C) 2010 OSA

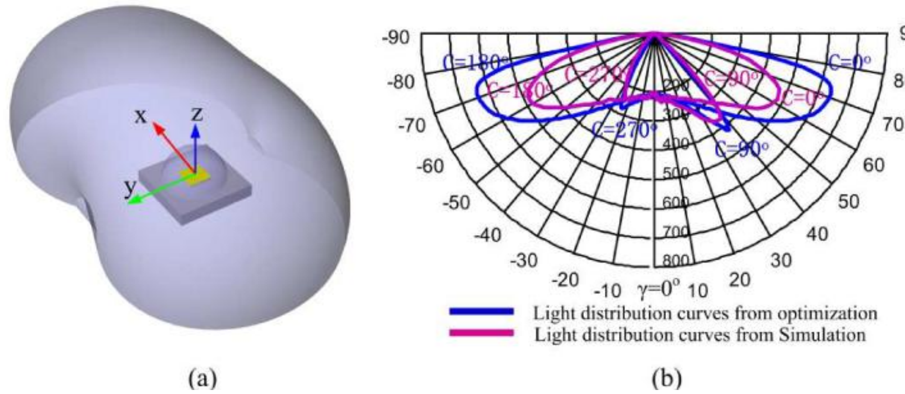

Fig. 7. (a). The original lens model with an LED source. (b).Light distribution curves derived from the simulation results of the original lens and the optimized illuminance distribution. The flux is unified into 1000lm

Table 2 shows the lighting parameters calculated from the simulation results of the original lens model. If the average luminance values are maintained at 1.5cd/m^2, flux of more than 600lm may be wasted because of about 12% lower Q values than optimized ones. The waste of flux can be approximately calculated as Eq. (22):

$$Flux_{waste} = (E_{avopti} - E_{avsimu}) \times W \times S \Big|_{L_{av}=1.5cd/m^2} \tag{22}$$

wherein E_{avopti} and E_{avsimu} are the optimized and simulated average illuminance values, respectively; W and S denote the road width and mounting space, respectively.

Table 2. Lighting parameters calculated from the simulation results of the original lens model

Observer position	L_{av}(cd/m^2)	U_0	U_L	TI(%)	E_{av}(lx)	E_0	Q(L_{av}/E_{av})
(−60.000, 1.875,1.500)	1.50	0.60	0.76	8.10	21.05	0.652	7.12×10^{-2}
(−60.000, 5.625,1.500)	1.50	0.60	0.79	5.47	19.49	0.652	7.70×10^{-2}

As Fig. 8 illustrate, Q values of the simulation results are gradually approaching the optimized ones as the iteration numbers increase; and after five times iteration, they become saturated.

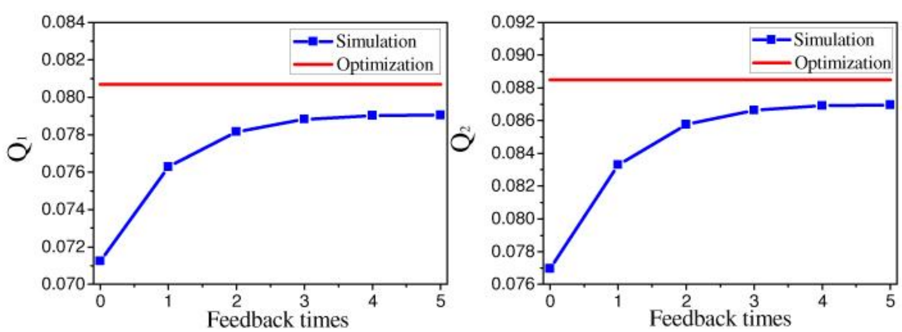

Fig. 8. Q values change with feedback times, which are calculated with the observer's position at (a) (−60m, 1.875m, 1.5m) and (b) (−60m, 5.625m, 1.5m).

Figure 9(a) shows the final lens model after five times iteration, and it's dimension (central length, central width and central height) is 17.64mm × 7.96mm × 6.47mm. It's light

#133129 - $15.00 USD Received 9 Aug 2010; revised 18 Sep 2010; accepted 22 Sep 2010; published 1 Oct 2010
(C) 2010 OSA

distribution curves, which have approximate shape as the optimized ones, are shown in Fig. 9(b).

Table 3 shows the lighting parameters calculated from the final simulation results, and they are close to the optimization results shown in Table 1.

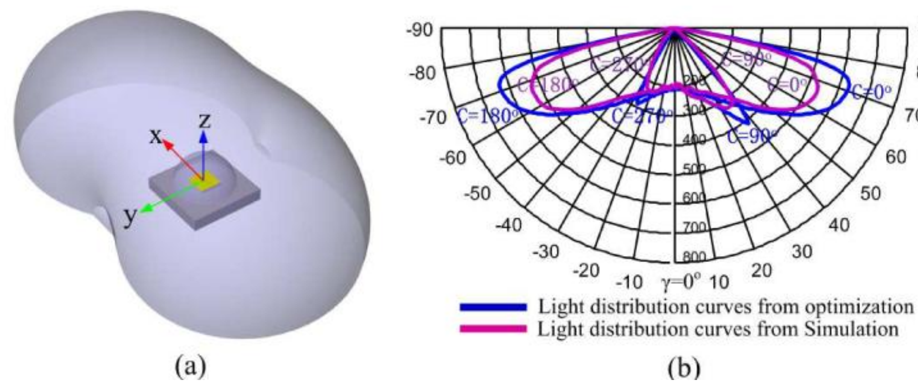

Fig. 9. (a). The final lens model after six times feedback with an LED source. (b). Light distribution curves derived from the simulation results of the final lens and the optimized illuminance distribution. The flux is unified into 1000lm

Table 3. Lighting parameters calculated from the simulation results of the final lens model

Observer position	$L_{av}(cd/m^2)$	U_0	U_L	TI(%)	$E_{av}(lx)$	E_0	$Q(L_{av}/E_{av})$
(–60.000, 1.875,1.500)	1.50	0.56	0.72	10.06	18.98	0.71	7.90×10^{-2}
(–60.000, 5.625,1.500)	1.50	0.55	0.79	6.73	17.25	0.71	8.69×10^{-2}

The luminance distributions on C2 road perceived by the observers on two positions are shown in Figs. 10. “Zebra effect” is virtually eliminated because of the improvement in the longitudinal road surface luminance uniformity U_L.

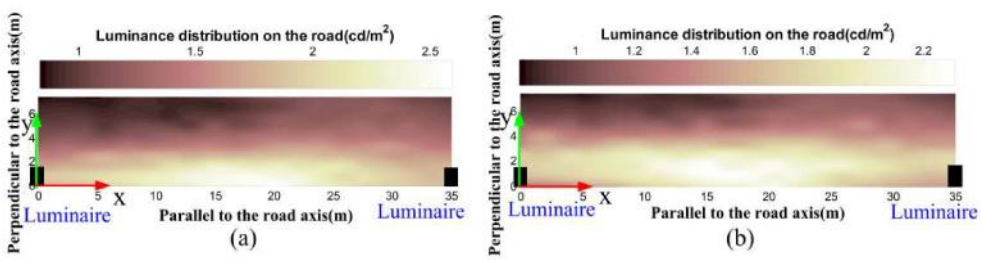

Fig. 10. Luminance distributions on C2 road perceived by observer at (a) (–60m, 1.875m, 1.5m) and (b) (–60m, 5.625m, 1.5m).

3.3 Sensitivity analysis

Since the luminaires’ installation accuracy can’t be guaranteed because of the complexity of the road, sensitivity is very important for road lighting design. In this section, sensitivity analysis is concerned with the influences of the mounting spaces and the mounting angles on the lighting parameters U_0, U_L, TI and Q.

Figures 11 show the effects of the mounting space S on the lighting parameters, wherein U_{01}, U_{L1}, TI_1, Q_1 and U_{02}, U_{L2}, TI_2, Q_2 are calculated with the observer’s position at (–60m, 1.875m, 1.5m) and (–60m, 5.625m, 1.5m), respectively. U_{01} and U_{02} change little as S increases, and always satisfy the lighting requirements. U_{L1} is slightly lower than 0.7 when S = 40m, but U_{L2} is not sensitive to S and always higher than 0.7. TI_1 seems more sensitive to S than U_0 and U_L, and its maximum value is 11.26% when S = 37.5m. As S increases from 30m to 40m, Q_1 slightly increases from 7.79×10^{-2} to 7.97×10^{-2} and Q_2 slightly increases from 8.60×10^{-2} to 8.75×10^{-2}.

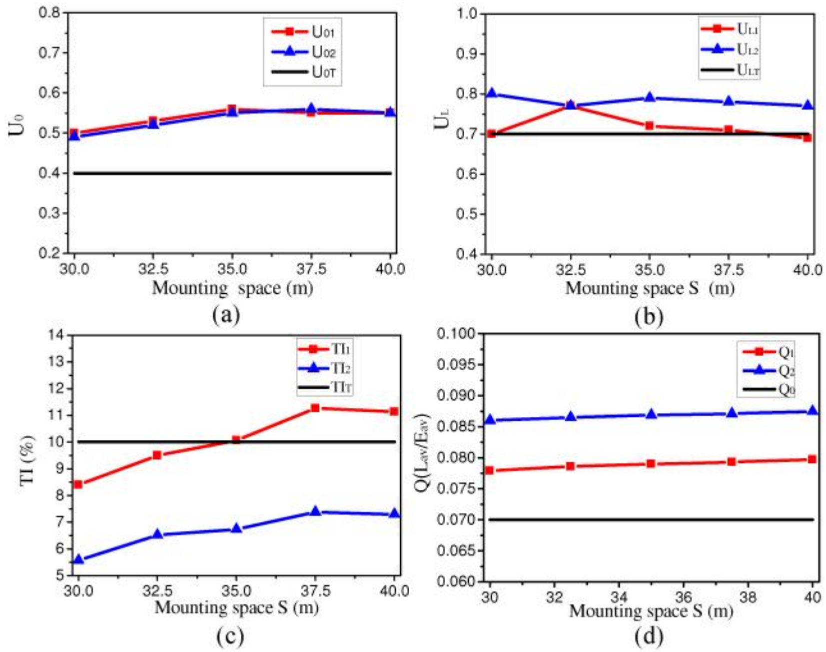

Fig. 11. Effects of the mounting space on the lighting parameters (a) U_0, (b) U_L, (c) *TI* and (d) *Q*.

The effects of the mounting angle θ on the lighting parameters are shown in Figs. 12. When θ changes from 0° to 10°, U_0, U_L and TI_2 change within the lighting requirements. TI_1 increases from 10.06% to 10.92% as θ increases, which is slightly higher than the lighting standard (10%). As θ increases from 0° to 10°, Q_1 slightly increases from 7.90×10^{-2} to 8.16×10^{-2}, and *Q2* slightly increases from 8.69×10^{-2} to 9.01×10^{-2}.

#133129 - $15.00 USD Received 9 Aug 2010; revised 18 Sep 2010; accepted 22 Sep 2010; published 1 Oct 2010
(C) 2010 OSA

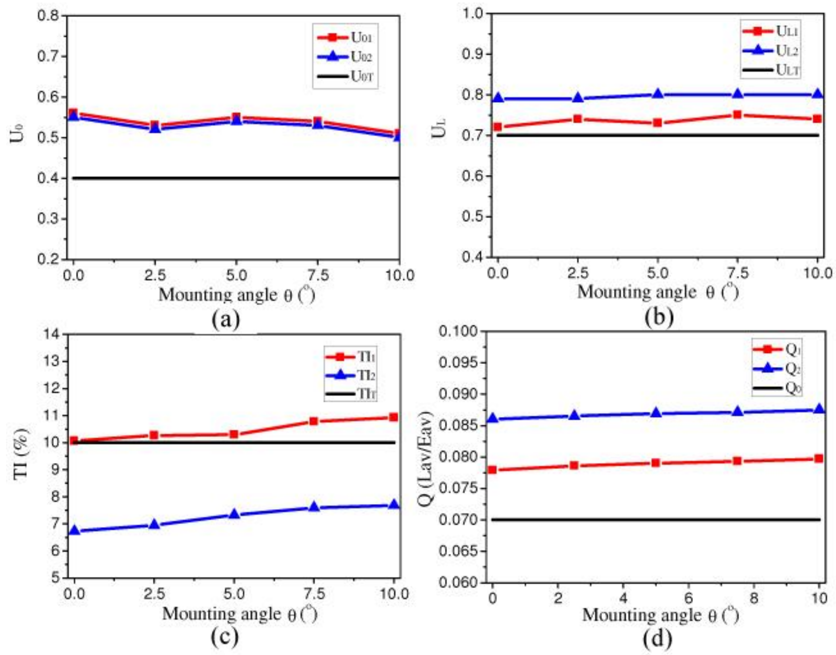

Fig. 12. Effects of the mounting angle on the lighting parameters (a) U_0, (b) U_L, (c) TI and (d) Q.

4. Conclusion

We demonstrate a systematic method of designing an optical system for road lighting using an LED and a freeform lens. The proposed design method takes account of the luminance characteristics of the road surface, the energy efficiency of the system, the glare problem of the luminaire and the effects of four adjacent luminaries illuminating a single road surface. Once the geometrical parameters (the mounting height, the mounting space and the road width, etc.) are fixed, optimized illuminance with a polynomial of cosine functions along the road direction can be obtained by maximizing Q as well as satisfying the lighting requirements provided by CIE Then, a smooth freeform lens with this optimized illuminance distribution is constructed based on the variable separation method. Since the extended light source and freeform surface errors have more effect on the lighting performance, the simulation results may have large deviations from the given illuminance. The lens model is modified with the simulation results by employing feedback functions until the simulation results approach the optimized illuminance. Lighting parameters calculated from the final simulation results show that we can obtain an energy efficient freeform optical system as well as satisfying the lighting requirements provided by CIE. This method can also be applied on other road surfaces with tested tables of the reduced luminance coefficients.

Acknowledgments

This work was supported by the National Natural Science Foundation of P. R. China (under Grant Nos. 60536020, 60723002, 50706022 and 60977022), the “973” Major State Basic Research Project of China (Nos. 2006CB302800 and 2006CB921106), the “863” High Technology Research and Development Program of China (Nos. 2007AA05Z429 and 2008AA03A194),Beijing Natural Science Foundation (No. 4091001), and the Industry, Academia and Research combining and Public Science and Technology Special Program of Shenzhen (No. 08CXY-14), Open Program of State Key Lab of Integrated Optoelectronics of China.