Light intensity distribution optimization for tunnel lamps in different zones of a long tunnel

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Abstract: The light distributions in different tunnel zones have different requirements in order to meet the driver's visual system. In this paper, the light intensity distributions of tunnel lamps in different zones of a long tunnel are optimized separately. A common nonlinear optimization approach is proposed to minimize the consuming power as well as satisfy the luminance and glare requirements both on the road surface and on the wall set by International Commission on Illumination (CIE). Compared with that of the reported linear optimization method, the optimization model can save energy from 11% to 57.6% under the same installation conditions.

OCIS codes: (080.4298) Nonimaging optics; (220.2945) Illumination design; (330.4595) Optical effects on vision.

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1. Introduction

Tunnel is a structure over a roadway completely enclosed except for openings at the entrance and exit. As our road networks become more and more crowded, the use of tunnels is expanding. Within tunnels, reliable performance of the lighting system is critical in order to satisfy the human visual system. The adaptation process of the human visual system is not instantaneous, the greater the difference of lighting level between outside and inside the tunnel is, the longer the adaptation time will be cost. Thus, lighting at the tunnel entrance must be strong enough to avoid the 'black hole' effect drivers experience when traveling from a very bright external light level to a comparably darker level. Besides, the lighting system should be carefully designed so that the drivers are able to detect any obstacles from a distance equals to the stopping distance from the tunnel portal [1–3].

In order to provide scientific and rational illumination, several requirements for the lighting performance in tunnels are specified in publications of the International Commission on Illumination (CIE) [2, 4]. CIE guidance (CIE 88-2004) states that the amount of light required within a tunnel is dependent on the level of light outside and the point inside the tunnel in which visual adaptation of the users must occur [2]. There are 5 key areas defined in CIE 88-2004 should be considered when designing the lighting of a tunnel: the access zone, the threshold zone, the transition zone, the interior zone and the exit zone. The access zone is the part of the open road immediately outside the tunnel portal, while the other four zones are inside the tunnel. For ideal tunnel lighting, the light technical parameters specified by the CIE in all the tunnel zones should be satisfied with minimum luminous flux, which means the electrical power should be minimized under the same condition.

Therefore, the design of light intensity distribution of tunnel lamp is a complex optimization problem as too many constraints need to be satisfied. There have been several researches on the light distribution designs of lamps especially for road and tunnel lighting [5–11]. A linear optimization method had been put forward by Pachamanov *et al.* to minimize the luminous flux inside the road surface for road and tunnel lighting [8]. However, only two luminaires parallel to the road were taken into account, and none attention was paid to the light distribution outside the road, such as the wall of tunnel, which may cause local optima but not global optimum. Feng *et al.* had proposed an efficient optimization approach to maximize Q (the ratio of the average luminance to the average illuminance), in which the road surface illuminance with a polynomial of cosine functions along the road was established to get smooth light distribution curves [9]. Hu *et al.* had raised an optimization method to achieve highest illuminance and luminance uniformity of the road surface in LED road lighting [10]. However, in both optimization methods, the light distribution was on parallel to the road axis. The distribution perpendicular to the road axis on the road was not well optimized. Thus, these previous results could not be applied for tunnel lighting very well. Further studies based on the tunnel characteristics are still necessary.

In this paper, a nonlinear optimization approach for light intensity distribution of tunnel lamps is proposed to minimize the luminous flux as well as satisfying the luminance and glare requirements set by CIE. The light technical parameters both on the road surface and on the wall of tunnels are considered in the optimization model. The light intensity distributions for lamps in different tunnel zones are obtained, and the optimization results are compared with that of a linear optimization method.

2. Long tunnel lighting requirements

As defined in CIE 88-2004, the road tunnels are usually subdivided into long tunnels and short tunnels. Some tunnels are designated as long tunnels if the drivers cannot see the exit from a point in front of the tunnel. In the long tunnel, good tunnel lighting requires that lighting levels should match with the adaptation level of the drivers' eyes. This adaptation level changes gradually while drivers travel through the tunnel. The luminance values on the road in the access zone, the threshold zone, the transition zone, the interior zone and the exit zone are different, which are expressed as L_{20}, L_{th}, L_{tr}, L_{in}, and L_{ex} as shown in Fig. 1. Here, the luminance L_{20} in the access zone is defined as the average of the luminance values measured in a conical field of view, subtending an angle of 20° (2 x 10°), by an observer located at the reference point and looking towards a centered point at a height equal to one quarter of the height of the tunnel opening [2]. In the practical tunnel lighting design, the luminance curve at threshold and transition zones can be replaced by a step curve as shown in Fig. 1 [4].

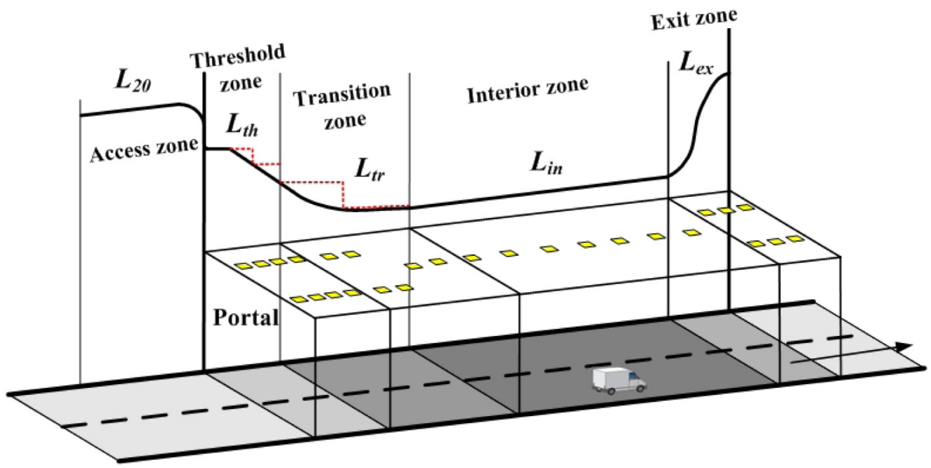

Fig. 1. The five tunnel zones of a long tunnel for lighting design.

Except for the luminance levels, there are some other light technical parameters should be considered in the lighting design, such as the overall uniformity, longitudinal uniformity and glare factor. All these light technical parameters are calculated based on a specified region, which should be designated firstly.

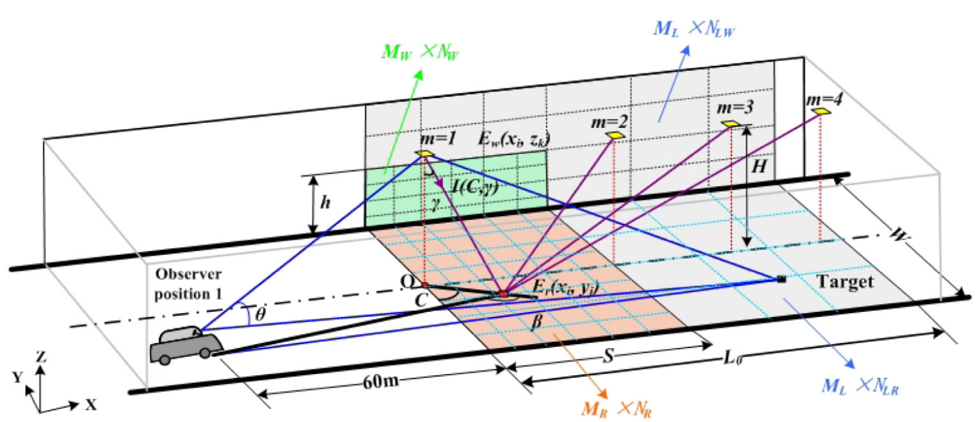

Fig. 2. Illustration of the calculation for tunnel lighting.

As shown in Fig. 2, the road surface between two adjacent luminaires is usually set as the calculation regions to calculate the light technical parameters on the road (orange region). The road width, the mounting space between two adjacent luminaires and the mounting height of luminaires are W, S and H. The region's edge lines perpendicular to the road axis and the observer position is 60m in the front of the luminaire 1 [12]. The calculation region is equidistantly separated into $M_R \times N_R$ rectangular cells, and coordinates (x_i, y_j) are used, where

x, y denote the coordinates parallel and perpendicular to the road axis, $i = 1, 2, \ldots, M_R$, $j = 1, 2, \ldots, N_R$. For the calculation of total luminous flux of luminaire, a region with length L_0 and width W on the road and height H on the wall is considered to collect almost all lights.

Once the parameters of H, S, W and the position of the observer are determined, the angles C, γ, β shown in Fig. 2 and the reduced luminance coefficient r can be expressed as functions of x_i and y_j. The luminance $L_r\,(x_i, y_j)$ on the road can be written as [12]

$$L_r(x_i, y_j) = \sum_{m=1}^{M} \frac{r_m(\beta_m(x_i, y_j), \gamma_m(x_i, y_j)))}{10^4 \cos^3 \gamma_m(x_i, y_j)} E_{rm}(x_i, y_j), \tag{1}$$

where $E_{rm}\,(x_i, y_j)$ is the illuminance on (x_i, y_j) unit cell produced by the m-th luminaire on the road, $m = 1, 2 \ldots M$. $r_m\,(\beta_m(x_i, y_j), \gamma_m(x_i, y_j))$ is the reduced luminance coefficient. CIE 144-2001 provides tables with values for $r(\beta, \gamma)$ for typical road surfaces which are divided into R1, R2, R3 and R4 according to the reflection properties of the road surface [13]. β is the angle between the vertical plane C of the light intensity vector towards the unit area under consideration and the observation plane, and γ is the angle between the light intensity vector towards the given unit area and the vertical axis of the luminaire (Fig. 2). Tunnel lighting on the road can be normally specified by the following photometric quality characteristics.

The average road surface luminance $L_{road\cdot av}$ is obtained as [12]:

$$L_{road.av} = \frac{\sum_{i=1}^{M_R} \sum_{j=1}^{N_R} L_r(x_i, y_j)}{M_R N_R}. \tag{2}$$

The overall road surface luminance uniformity $U_{road\cdot O}$, and the longitudinal road surface luminance uniformity $U_{road\cdot L}$ are given by [12]:

$$U_{road.O} = \frac{\min(L_r(x_i, y_j))}{L_{road.av}}, i = 1, 2 \ldots, M_R, j = 1, 2 \ldots, N_R, \tag{3}$$

$$U_{road.L} = \frac{\min(L_r(x_i, y_{middle}))}{\max(L_r(x_i, y_{middle}))}, i = 1, 2 \ldots, M_R, \tag{4}$$

where $\min(L_r(x_i, y_j))$ is the minimum value of the road surface luminance in the calculation region, $\min(L_r(x_i, y_{middle}))$ and $\max(L_r(x_i, y_{middle}))$ are the minimum and maximum luminance values on the middle lane line passing through the position of the observer (y_{middle}).

The glare factor TI (threshold increment) is a function of equivalent veiling luminance L_v and the average road surface luminance $L_{road\cdot av}$. The veiling luminance L_v is [14]:

$$L_v = 3 \times 10^{-3} \sum_{m=1}^{M} \frac{E_{Vm}}{\theta_m{}^2}, \tag{5}$$

where E_{Vm} is the illuminance produced by the m-th luminaire into the observer's eyes in the plane perpendicular to the observer's line of sight, θ_m is the angle between the line of the observer's sight and the center of the m-th luminaire, as shown in Fig. 2. The glare factor TI is determined by [14]:

$$TI = \frac{65 L_v}{L_{road.av}{}^{0.8}}, \tag{6}$$

for $L_{road\cdot av} \leq 5\text{cd/m}^2$ and

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$$TI = \frac{95 L_v}{L_{road.av}{}^{1.05}}, \tag{7}$$

for $L_{road \cdot av}$>5cd/m^2.

For tunnel lighting, the luminance of the tunnel walls is an important component for the quality of the tunnel lighting as well, since it is used for the detection of obstacles in the tunnel and contributes to the adaptation level and the visual guidance. The average luminance of the tunnel walls, up to at least a height of 2m, must be at least 60% of the average road surface luminance at the relevant location [2]. The calculation region for tunnel lighting on the wall is set between two adjacent luminaires as shown in Fig. 2 (green region). The wall is equidistantly separated into $M_W \times N_W$ rectangular cells, and coordinates (x_i, z_k) are used, in which $i = 1, 2, \ldots, M_W$, $k = 1, 2, \ldots, N_W$. The luminance $L_w (x_i, z_k)$ on the wall is [4]

$$L_w(x_i, z_k) = \frac{\rho_{wall}}{\pi} E_w(x_i, z_k), \tag{8}$$

$E_w(x_i, z_k)$ is the illuminance on (x_i, z_k) unit cell on the wall, and ρ_{wall} is the reflection coefficient on the wall.

Tunnel lighting on the walls is normally specified by the photometric quality characteristics including the average wall luminance $L_{wall \cdot av}$ and the overall wall luminance uniformity $U_{wall.O}$.

$$L_{wall.av} = \frac{\sum_{i=1}^{M_W} \sum_{k=1}^{N_W} L_w(x_i, z_k)}{M_W N_W}, \tag{9}$$

$$U_{wall.O} = \frac{\min(L_w(x_i, z_k))}{L_{wall.av}}, i = 1, 2..., M_W, k = 1, 2..., N_W, \tag{10}$$

where $\min(L_w(x_i, z_k))$ is the minimum value of wall luminance.

Similar to road lighting, the light technical parameters of tunnel lighting on the road surface should meet the road lighting requirements, which can be summarized as follows.

$$L_{road.av} \geq L_{road.av}{}^T, \tag{11}$$

$$U_{road.O} \geq U_{road.O}{}^T, \tag{12}$$

$$U_{road.L} \geq U_{road.L}{}^T, \tag{13}$$

$$TI \leq TI^T. \tag{14}$$

The superscript T denotes parameter values specified in [2]. Except for the lighting requirements on the road surface, the light technical parameters on the wall surface of the tunnel should be considered in the calculations as well, which making the problem more complicated. The restrictions on the walls for tunnel lighting are

$$L_{wall.av} \geq q \times L_{road.av}, \tag{15}$$

$$U_{wall.O} \geq U_{wall.O}{}^T, \tag{16}$$

where q is the coefficient of average wall luminance to average road luminance.

For tunnel lighting designs, the restrictions given in Eq. (11) to (16) should all be satisfied.

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3. Formulation and solution of the optimization problem

With the development of new light sources such as LEDs, more and more tunnel lighting systems will be upgraded with these energy saving sources [9, 15]. The easiest way is to replace the old lamps with new ones in the original installation locations. Therefore, the locations of the lamps are the fixed parameters in the optimization model. In order to increase the efficiency of the tunnel lighting, it is important to provide an optimized light intensity distribution with the minimum possible flux of the lamps under considerations that the restrictions on L_{av} and all other conditions are satisfied. Since the luminous flux is related to the electrical power of the lamp, a minimum luminous flux also ensures maximum energy efficiency of the lighting installation. It should be noted that the objective function in the optimization model is the total luminous flux of the lamps but not only the partial luminous flux in the area of the road between two luminaires as in [8], which may results in global but not local optimum. Therefore, we employ a large enough region as shown in Fig. 2 (gray region) to collect almost all light emitting from a luminaire for total luminous flux calculation. The region on the road is with length L_0 and width W, which is equidistantly separated into $M_L \times N_{LR}$ cells. The region on the wall is with length L_0 and height H, which is equidistantly separated into $M_L \times N_{LW}$ cells. The total luminous flux Φ is the summation of luminous intensity $I(\mathrm{C}, \gamma)$ over all unit solid angle $d\omega$ on the unit areas dS. The objective function in the optimization model is to minimize the total luminous fluxΦ, which is

$$\min \Phi = \sum_{i=1}^{M_L} \sum_{j=1}^{N_{LR}} I(C(x_i, y_j), \gamma(x_i, y_j)) d\omega(x_i, y_j) + 2 \times \sum_{i=1}^{M_L} \sum_{k=1}^{N_{LW}} I(C(x_i, z_k), \gamma(x_i, z_k)) d\omega(x_i, z_k), \tag{17}$$

in which

$$\begin{gathered} d\omega(x_i, y_j) = \frac{dS \cos^3 \gamma(x_i, y_j)}{H^2} \\ i = 1, 2..., M_L, \; j = 1, 2..., N_{LR}, \end{gathered} \tag{18}$$

$$\begin{gathered} d\omega(x_i, z_k) = \frac{dS \cos^2 \gamma(x_i, z_k) \sin \gamma(x_i, z_k)}{H^2} \\ i = 1, 2..., M_L, k = 1, 2..., N_{LW}. \end{gathered} \tag{19}$$

The restrictions can be rewritten as

$$s.t. \quad \frac{\sum_{i=1}^{M_R} \sum_{j=1}^{N_R} L_r(x_i, y_j)}{M_R N_R} \geq L_{road.av}{}^T, \tag{20}$$

$$\frac{\min(L_r(x_i, y_j))}{L_{road.av}} \geq U_{road.O}{}^T, i = 1, 2..., M_R, j = 1, 2..., N_R, \tag{21}$$

$$\frac{\min(L_r(x_i, y_{middle}))}{\max(L_r(x_i, y_{middle}))} \geq U_{road.L}{}^T, i = 1, 2..., M_R, \tag{22}$$

$$\frac{k_{TI} \times 3 \times 10^{-3} \sum_{m=1}^{M} \frac{E_{Vm}}{\theta_m{}^2}}{L_{road.av}{}^{n_{TI}}} \leq TI^T, \tag{23}$$

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$$\frac{\sum_{i=1}^{M_W}\sum_{k=1}^{N_W} L_w(x_i,z_k)}{M_W N_W} \geq q\frac{\sum_{i=1}^{M_R}\sum_{j=1}^{N_R} L_r(x_i,y_j)}{M_R N_R}, \tag{24}$$

$$\frac{\min(L_w(x_i,z_k))}{L_{wall.av}} \geq U_{wall.O}{}^{T}, i=1,2...,M_W, k=1,2...,N_W, \tag{25}$$

where k_{TI} is 65 for $L_{road\cdot av} \leq 5\text{cd/m}^2$ and 95 for $L_{road\cdot av} \geq 5\text{cd/m}^2$. n_{TI} is 0.8 for $L_{road\cdot av} \leq 5\text{cd/m}^2$ and is 1.05 for $L_{road\cdot av} \geq 5\text{cd/m}^2$.

It is almost impossible to solve the optimization problems directly because of too much unknown factors of luminous intensities. The number of values for the light intensity is not sufficient to construct complete and smooth light distribution curves even when a large number of unit areas are considered [8, 9].

From Eq. (17)-(19), objective function of Eq. (17) can be rewritten as:

$$\min\Phi = \sum_{i=1}^{M_L}\sum_{j=1}^{N_{LR}} E_r(x_i,y_j)dS_r + 2\times\sum_{i=1}^{M_L}\sum_{k=1}^{N_{LW}} E_w(x_i,z_k)dS_w, \tag{26}$$

in which

$$\begin{aligned} &E_w(x_i,z_k) = \frac{H^2\tan\gamma_k(x_i,z_k)}{(H-z_k)^2}E_r\left(\frac{H}{H-z_k}x_i, \frac{H}{H-z_k}\frac{W}{2}\right). \\ &i=1,2...,M_L, k=1,2...,N_{LW} \end{aligned} \tag{27}$$

$E_r(x_i,y_j)$ and $E_w(x_i,z_k)$ are the illumination on the road and on the wall. dS_r and dS_w are the unit areas on the road and on the wall.

Since the calculations of all lighting parameters are based on the given illumination distribution on the road, a suitable expression of illumination distribution should be proposed firstly. According to CIE 88-2004 and CEN CR 14380-2003, there are two artificial lighting systems in common use: the symmetrical lighting system and the counter beam lighting system [2, 4]. The luminance of counter beam lighting system is usually significantly higher than that with symmetrical lighting. However, the black hole effects can be more pronounced than that with symmetrical tunnel lighting. Besides, the shading effect from direct light caused by high lorries will tend to mask following vehicles [2]. Thus we take the symmetrical lighting system for our optimization design. For the symmetrical lighting system, a polynomial of cosine function for illuminance distribution on the road taking account of x, y and tilt angle constant φ can be introduced as Eq. (28) [9, 11].

$$E_r(x,y) = \sum_{u=0}^{U}\sum_{v=0}^{V} a(r,s)\cos^u(\tan^{-1}(\frac{x}{H}))\cos^v(\tan^{-1}(\frac{y}{H})+\varphi), \tag{28}$$

where U, V are the numbers of powers u, v. $a(u, v)$ is the illuminance coefficient.

The expression is more appropriately and practically describing the characteristic of symmetrical lighting system defined in CEN CR 14380-2003 than other previous publications [9, 11]. It is symmetrical in the 0°/180° C-plane. Besides, an angle φ is taking into consideration depended on the mounting conditions. When the luminaire is arranged in the center of the lane, φ is equal to zero, which means that the light distribution is symmetrical in relation to the 90°/270° C-plane. Otherwise φ is equal to the actual installation angle between the luminaire and the wall. It is reasonable to choose this representation for several reasons. Firstly, the distribution of cosine functions is more suitable for radiation pattern of the tunnel lighting source and in favor of optimization of the lighting distribution [16]. Secondly, the smoothly decreasing distribution of cosine functions can easily balance all the lighting parameters, guarantee better tolerances and obtain smooth light distribution curves. Thirdly, the solution returned by the solver immediately allows all the values for the intensities to be obtained in the C–γ format recommended by the CIE, since large region is considered to collect almost all light emitting from one luminaire. Lastly, the number of variables can be greatly reduced and the optimization problem formulation is greatly simplified.

Then, the optimization problems described in the previous section can be simplified into a nonlinear model with polynomials of different powers U, V and coefficient $a(u, v)$. For a defined region, the relative coordinates of the observer, the luminaires and the points on the road and walls are determined, by which the angles β and γ can be calculated as well. The luminance coefficient $r(\beta, \gamma)$ can be obtained by q-body tables available in CIE publications with interpolation method. Then, the lighting parameters for the vertical illuminance, the veiling luminance and wall luminance can all be calculated with $r(\beta, \gamma)$. The power U and V can be identified with an iterative method. The initial iterative values of U and V are set as 1. The optimization solver Lingo (Linear Interactive and General Optimizer) is employed to find the optimal values for the coefficients $a(u, v)$. After the first iteration, the values of U and V are increasing with arithmetic progression by a tolerance of 1. The coefficients $a(u, v)$ are sequentially acquired by Lingo. At the same time, the total luminous flux of a luminaire is also computed in each iteration with Eq. (26) and Eq. (27). The iteration is ended when the allowable error of the total luminous flux between two adjacent iterations is within 1%. So far, the satisfied values of U, V and $a(u, v)$ can be obtained in the nonlinear model.

4. Optimization design example

In order to solve the above model, the geometrical parameters of lamp installation locations should be given firstly, which are listed in Table 1. Most of the parameters are taken from [8], so that the optimized results can be compared under the same conditions. The road is one-way two-lane. There are two rows of luminaires in the threshold zone and exit zone, where the high luminance levels are needed. While in the transition zone and interior zone, the luminance requirements are relatively low, only one row of luminaires is arranged.

Table 1. Geometrical Parameters of Lighting Installations at Different Tunnel Zones

Tunnel zones	Lighting installation parameters					
	Mounting height(m)	Mounting space(m)	Road width(m)	Mounting rows	Distance between luminaires and curb(m)	Average luminance factor
Beginning of threshold zone	5.5	4	8	2	2.5	0.07
Second half of threshold zone	5.5	5	8	2	2.5	0.07
Middle of transition zone	5.5	15	8	1	4	0.07
Interior zone	5.5	18	8	1	4	0.07
Exit zone	5.5	6	8	2	2.5	0.07

Then, the position of calculation points can be defined base on the geometrical parameters. The region on the road is divided into 18 × 14 rectangular cells and on the wall into 18 × 5 rectangular cells to calculate the lighting parameters. The total luminous flux calculation region on the road is divided into 200 × 16 rectangular cells with the length L_0 equal to 100m, and on the wall into 200 × 10 rectangular cells.

Table 2. Lighting Parameters Obtained from Nonlinear and Linear Optimization Method at Different Zones

Lighting parameters	Beginning of threshold zone			Second half of threshold zone			Middle of transition zone			Interior zone		Exit zone	
	CIE	LM	NLM	CIE	LM	NLM	CIE	LM	NLM	CIE	NLM	CIE	NLM
$\boldsymbol{\Phi}$(klm)	null	55	31.9	null	55	23.3	null	55	48.8	null	17.4	null	14.3
$L_{road.av}$(cd/m^2)	90	98.37	98.37	36	58.83	58.83	9	19.68	19.68	6	6	30	30
$U_{road.O}$	0.4	0.5	0.4	0.4	0.45	0.4	0.4	0.41	0.5	0.4	0.4	0.4	0.4
$U_{road.L}$	0.6	0.89	0.9	0.6	0.89	0.9	0.6	0.62	0.8	0.6	0.68	0.6	0.9
TI (100%)	15	7.44	7.7	15	10.69	9.3	15	20.7	14	15	9	15	9.3
$L_{wall.av}$(cd/m^2)	54	null	77	21.6	null	55.8	5.4	null	34.2	3.6	5.5	18	23
$U_{wall.O}$	0.4	null	0.55	0.4	null	0.49	0.4	null	0.43	0.4	0.41	0.4	0.44

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With the mounting conditions listed in Table 1, the optimized light intensity distribution for lamps in the beginning of threshold zone, the second half of the threshold zone, the middle of transition zone, the interior zone and the exit zone are obtained and plotted in Fig. 3. It is obvious that the light intensity distributions are different in different zones. That is, one single type of light distribution is not applicable to achieve the most energy-saving tunnel lighting for all zones. In order to compare with the former work, we further calculate the lighting parameters of luminaires from the optimized light distributions at different zones. The data obtained from two different optimal methods (linear method (LM) and nonlinear method (NLM)) are listed in Table 2. For better comparison, the lighting parameters specified by CIE are listed in the Table 2 as well [8].

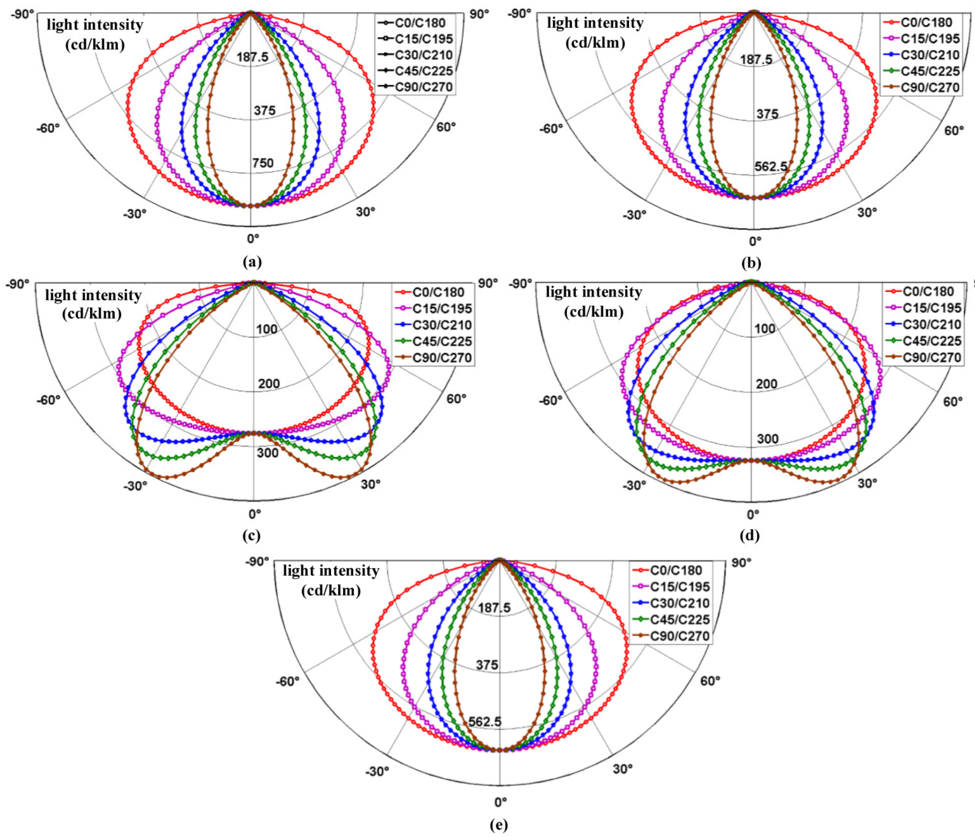

Fig. 3. Optimal light distributions at different zones. (a) the beginning of the threshold zone. (b) the second half of the threshold zone. (c) the middle of the transition zone. (d) the interior zone. (e) the exit zone.

The results in Table 2 indicate that for achieving the same luminance on the road surface at the beginning of the threshold zone, luminaire with LM method needs the total luminous flux of 55klm, which is 42% higher than that of with NLM method. While in the second half of the threshold zone, luminous flux of luminaire with LM method is 57.6% higher than that of with NLM method. All the lighting parameters such as $U_{road.O}$, $U_{road.L}$ and TI are within the required norms. In the middle of the transition zone, luminous flux of luminaire with LM method is 11% higher than that of with NLM method, which is relatively smaller than that in other zones. However, the threshold increment TI of glare factor is reach up to 20.7%, which is higher than the required TI of 15% in [8]. The corresponding value of TI is 14% for luminaire with our NLM method, meeting the required norms. Meanwhile, the light technical parameters on the wall are also taken into consideration in the calculation, which are not considered in the former works. Results show that the luminance $L_{wall.av}$ and the overall wall luminance uniformity $U_{wall.O}$ of luminary with NLP method can satisfy the CIE requirements very well as listed in Table 2.

From Figs. 3(a)-3(e), we can see that the light intensity distributions are different in different zones at the fixed mounting conditions. However, there are various tunnels and different mounting conditions, which needs vast types of tunnel lamps to achieve the most energy-saving. It is virtually impossible to make so many types of lamps because of the high manufacturing costs for a new type of product. The lamps can be replaced with the similar light intensity distribution. The optimized results as shown in Fig. 3 indicate that the lamps in the beginning of the threshold zone, the second half of the threshold zone and the exit zone have similar light intensity distributions. It is the same for the lamps in the middle of the transition zone and the interior zone.

Table 3. Comparison of Lighting Parameters with the Different Optimal Light Distribution at the Same Zone

Lighting parameters	Beginning of threshold zone			Second half of threshold zone			Middle of transition zone		Interior zone		Exit zone		
	LD1	LD2	LD5	LD1	LD2	LD5	LD3	LD4	LD3	LD4	LD1	LD2	LD5
$\boldsymbol{\Phi}$(klm)	31.9	31.9	31.9	23.3	23.3	23.3	48.8	48.8	17.4	17.4	14.3	14.3	14.3
$L_{road.av}$(cd/m^2)	98.37	100.62	100.32	57.5	58.83	58.66	19.68	20.2	6.4	6	29.43	30.1	30
$U_{road.O}$	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.4
$U_{road.L}$	0.9	0.9	0.9	0.9	0.9	0.9	0.8	0.7	0.6	0.68	0.9	0.9	0.9
TI (100%)	7.7	9.3	9.2	7.5	9.3	9.6	14	12	10	9	7.6	9.3	9.3
$L_{wall.av}$(cd/m^2)	77	78.4	76.96	54.1	55.8	56.76	34.2	35	6	5.5	23.01	23.2	23
$U_{wall.O}$	0.55	0.55	0.56	0.46	0.49	0.48	0.43	0.42	0.46	0.41	0.42	0.43	0.44

In order to compare the lighting effects with the similar light intensity distribution, we further calculate the lighting parameters with different lamps in all zones. The results are shown in Table 3, in which LD1 to LD5 are lamps with optimized light distributions (LD) in the beginning of the threshold zone, the second half of the threshold zone, the middle of the transition zone, the interior zone and the exit zone, respectively. The total luminous flux is set as the same value for each case in the calculation. Results show that the lighting parameters calculated from LD1, LD2 and LD5 are almost the same, as well as those of LD3 and LD4. Therefore, two kinds of optimal light distribution are enough to obtain the most energy saving tunnel lighting in five different zones motioned above. This is helpful for further lighting design of the tunnel lamps.

5. Conclusion

A nonlinear model for the optimization of the lighting distribution of luminaires for tunnels has been presented in this article to obtain the most energy-saving light distributions as well as satisfying the lighting requirements provided by CIE in different zones of a long tunnel. Compared with the light distribution optimized with linear optimal method, the nonlinear optimal approach can save energy at least 11% and at most 57.6% than the former research in transition zone and in threshold zone, respectively. Therefore, the proposed optimization method can provide a common and efficient solution for tunnel lighting under fixed lamp installations.

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