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Quantitative evaluation of the discomfort glare of a tunnel pergola

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ABSTRACT

The light spot on the ground at the portal of a tunnel, which is caused by the sun shining on a pergola, consists of bright areas and dark areas, and it can cause a discomfort glare for drivers. In this study, in order to evaluate the level of discomfort glare, the bright areas were compared to lamps and the dark areas were compared to the backgrounds. Using Unified Glare Rating (UGR), which is used to evaluate the glare degree in lighting places, we established a quantitative evaluation method of the discomfort glare and derived the formulas that could calculate the UGR of the pergola with equal beam spacing and unequal beam spacing. In accordance with the formulas, the UGR of the two kinds of pergolas was calculated. The results showed that the UGR of the pergola with equal beam spacing was smaller than the UGR of the pergola with unequal beam spacing, demonstrating a less level of the discomfort glare. Furthermore, the relationship between the variations of the parameters of the pergola and the UGR was analyzed, which could provide references for the design of the pergola and the improvement of driving comfort.

1. Introduction

Glare, which is caused by the nonuniform distribution or the strong contrast of luminance, can cause discomfort or weaken the ability to distinguish details or objects (Kohko et al. 2015; Lehnert 2001). The glare is usually divided into a disability glare and a discomfort glare. A disability glare has a direct physiological relationship with the human eye, and it can reduce the visual ability. A discomfort glare only brings discomfort but does not reduce the visual ability (Lin et al., 2016).

In the field of highway traffic lighting, research on the discomfort glare has mainly focused on road lighting and automobile lighting. Kohko et al. (2015) studied the effect of light-emitting diode (LED) streetlights on the glare in a pedestrian area and proposed a new algorithm that evaluated the discomfort glare. Lin et al. (2015) examined the involuntary physiological responses to the discomfort of glare using new approaches for analysis: relative pupil size and speed of eye movement. Villa et al. (2017) investigated the level of the discomfort glare experienced by pedestrians under various urban LED luminaires through psychovisual experiments. Reagan and Brumbelow (2015) compared the perceived discomfort glare from an adaptive beam headlighting system with three low-beam-lighting configurations. Haycock et al. (2017) developed a novel glare simulator that was able to reproduce the effect of bright headlights from oncoming traffic using a novel hybrid display system, combining traditional projectors with panels of high-intensity LEDs mounted on a robotic actuator.

In the design of a tunnel, a pergola is always needed in order to reduce the luminance difference between the inside and outside of the tunnel. As a result, there will be the light spot on the ground when the sun is shining on the pergola. The light spot consists of bright and dark areas, leading to a contrast on the ground, which can cause a discomfort glare. However, the research on the glares of a pergola has mainly focused on disability glare (Jurado-Piña and Mayora, 2009; Jurado-Piña et al., 2010) and from the aspect of avoiding a flickering effect (Peña-García, 2018). Disability glare is caused by direct sunlight, and it may impair drivers' vision. The flickering effect is caused by the repetitions of the light signals within the pergola's area, and it may trigger seizures that are potentially dangerous situations, especially for photosensitive patients (Dondi et al., 2012). Though Gil-Martín et al. (2015) studied how to improve the nonuniform light distribution under a pergola, there was no quantitative study of the discomfort glare. In order to avoid the influence of discomfort glare on driving, it should be evaluated at the design stage.

In this study, the discomfort glare of the light spot of a pergola was analyzed, and the UGR was used to establish a quantitative algorithm for the glare. Additionally, the relationship between the parameters of the pergola and the UGR was analyzed, which could provide a reference

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Fig. 1. Pergola at the portal of a tunnel.

for the design of the pergola.

2. Form of the discomfort glare of a pergola

When a driver drives in and out of the tunnel, the sharp change of the luminance inside and outside the tunnel will produce the “bright-hole” and the “black-hole” effects, which will affect the driver′s visual recognition and lead to “bright adaptation” and “dark adaptation” (Schreuder, 1971; Zhigang et al., 2014). In order to reduce the luminance difference between the inside and the outside of a tunnel, a pergola is usually set at the portal of a tunnel (Jie et al., 2010), as shown in Fig. 1.

There are quite a few kinds of pergolas in accordance with the different materials of their superstructures (Wang, 2011), but they are alike in having a certain number of independent beams. When the sun shines on the beams, there is a light spot on the ground, which consists of dark and bright areas. In this study, the dark areas were compared to the background environment and the white areas were compared to the lamps. The alternating of the areas with different luminance created a contrast on the ground and caused a discomfort glare, affecting the driving comfort and reducing the drivers′ ability to distinguish the details of objects.

3. UGR algorithm

3.1. UGR definition

UGR is a psychological parameter used to measure the subjective response to light, which is emitted by a lighting device, in a visual environment with respect to the discomfort of human eyes (China Academy of Architectural Sciences, 2013). The UGR can be calculated with Eq. (1), in which L_b is the luminance of the background (cd/m^2), L_a is the luminance of each luminaire in the direction of the observer (cd/m^2), w is the solid angle formed by the luminescent part of the lamp to the observer′s eye (sr), n is the amount of the lamps, and P is the position index of each lamp:

$$UGR = 8\lg\frac{0.25}{L_b}\sum_{1}^{n}\frac{L_a^2 \mathrm{w}}{P^2} \tag{1}$$

w should be determined according to Eq. (2), in which A_p is the apparent area of the luminescent part of the lamp in the direction of the observer′s eyes (m^2) and r is the distance between the center of the luminescent part of the lamp and the observer′s eyes (m):

$$\mathrm{w} = \frac{A_p}{r^2} \tag{2}$$

The P was checked in *the position index table* in the *standard for lighting design of buildings (GB 50034-2004)* according to the position relation, namely, H/R and T/R, as shown in Fig. 2, in which (R, T, H) represents the coordinates at the center of the luminaire.

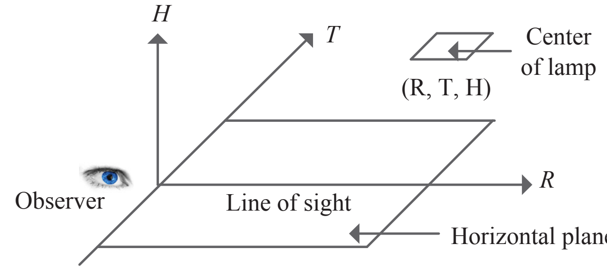

Fig. 2. Coordinate system of the location index with the observer position as the origin (R, T, H).

3.2. UGR algorithm of the pergola

3.2.1. Conversion of the parameters

It is easy to understand that the luminance of the bright areas or the dark areas of the light spot was constant, and the luminance ratio of the two areas was fixed. The relationship between the luminance of the two areas is shown in Eq. (3), in which L_a is the luminance of the bright areas, L_b is the luminance of the dark areas, and x is the luminance ratio:

$$L_a = \mathrm{x}L_b \tag{3}$$

However, the width of each area varied with the structure of the pergola. The relationship between the width of the two areas is shown in Eq. (4), in which a_i is the width of each dark area, b_i is the width of each bright area, y_i is the width ratio of each bright area and dark area, and i is the beam number from the outside to the inside of the tunnel:

$$\mathrm{b}_i = \mathrm{y}_i a_i \tag{4}$$

3.2.2. UGR algorithm of the pergola with unequal beam spacing

Fig. 3 shows a schematic diagram of the driver seeing the light spot. In the figure, the sun is shining perpendicularly to the pergola, and the z, h, d are the width of the beam, the thickness of the beam, and the beam spacing, respectively. The height of the eyes is 1.5 m for the ordinary drivers driving (Ministry of Transport of the People′s Republic of China, 2014). The horizontal distance between the eyes and the nearest dark area is 8.5 m. This distance was calculated according to the driver′ view in a 20° angle.

As mentioned above, the bright areas and the dark areas were treated as lamps and background, respectively. Subsequently, Eq. (1) could be converted to Eq. (5) using the parameters of the light spot, in which l is the road width, θ is the angle between the eyesight and the ground, n is the total amount of the beams, i is the beam number from the outside to the inside of the tunnel, and $sin\theta_i$ can be calculated with Eq. (6). Finally, Eq. (7) could be deduced:

$$UGR = 8\lg 0.25 L_a \mathrm{x}l\sum_{i=1}^{n}\frac{y_i a_i \sin^3\theta_i}{2.25P_i^2} \tag{5}$$

$$\sin\theta_i = \frac{1.5}{\sqrt{2.25 + (8.5 + \sum_{j=1}^{i} a_j + \sum_{j=1}^{i} b_j - \frac{b_i}{2})^2}} \tag{6}$$

$$UGR = 8\lg(L_a \mathrm{x}l\sum_{i=1}^{n}\frac{0.375 y_i a_i}{P_i^2\left(2.25 + (8.5 + \sum_{j=1}^{i} a_j + \sum_{j=1}^{i} b_j - \frac{b_i}{2})^2\right)^{\frac{3}{2}}}) \tag{7}$$

3.2.3. UGR algorithm of the pergola with equal beam spacing

In order to make the ambient luminance change slowly at the portal

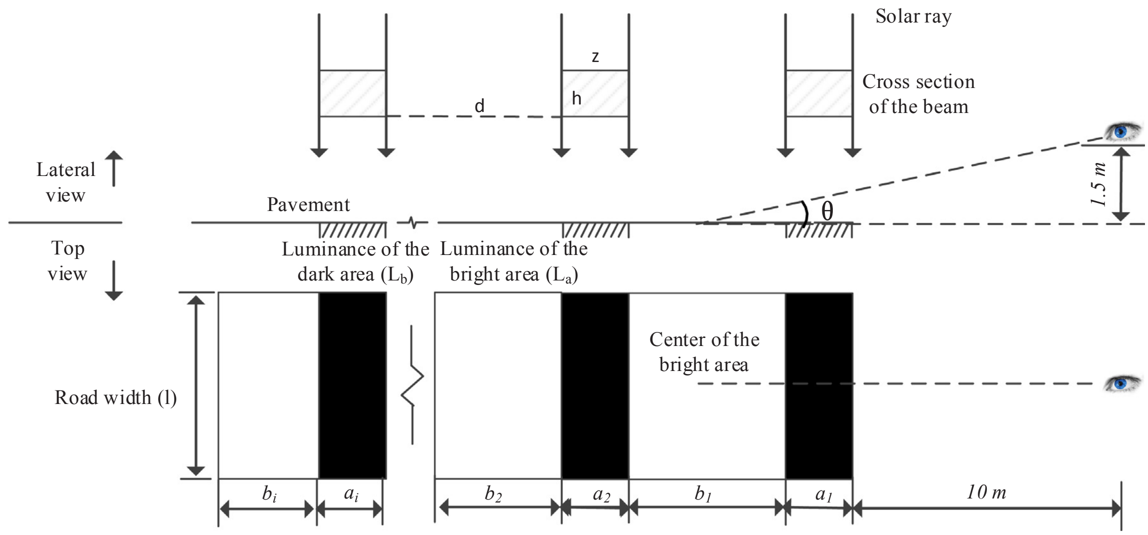

Fig. 3. Schematic of seeing the light spot.

of a tunnel, the pergolas are always designed with unequal beam spacing, which gradually becomes smaller from the outside to the inside of a tunnel. Eq. (7) describes the UGR algorithm of a pergola with variable beam spacing, when the beam spacing and the beam size of the pergola are constants; that is, *a* and *y* are fixed values. The UGR algorithm of the pergola with equal beam spacing can then be derived as shown in Eq. (8):

$$UGR = 8\lg\left(L_a x l \sum_{i=1}^{n} \frac{0.375ya}{P_i^2\left(2.25 + (8.5 + (y + 1)ia - \frac{b_i}{2})^2\right)^{\frac{3}{2}}}\right) \tag{8}$$

4. Calculation and comparison of the UGR

In order to compare between the UGR of the pergolas with equal beam spacing and unequal beam spacing, the UGR of the pergola with unequal beam spacing shown in Fig. 1 was calculated, and the UGR of the pergola with equal beam spacing was calculated using the same parameters except for the beam spacing.

4.1. Parameters

The pergola shown in Fig. 1 consisted of seventeen curved beams with a total length of 24 m. The internal contour of each beam was subject to the outline in the tunnel, the width of each beam is 350 mm, the beam spacing varied from 1800 mm to 300 mm in an arithmetic sequence from the outside of the tunnel inwards, as listed in Table 1. The one-way road was 9 m wide. When the sun was shining vertically, the width of the bright area on the road surface was the largest, which was equal to the beam spacing. The width of the dark area was the smallest, which was equal to the width of the beam.

The position index P was checked in *the position index table* in the *standard for lighting design of buildings (GB 50034-2004)* according to the

Table 1
Values of the beam spacing.

Beam spacing (mm)	1	2	3	4	5	6
	1800	1706	1613	1519	1425	1331
	7	8	9	10	11	12
	1238	1144	1050	956	863	769
	13	14	15	16	17	
	675	581	488	394	300	

Note: The beams were numbered 1–17 from the outside in.

values of H/R and T/R (China Academy of Architectural Sciences, 2013), Tables 2 and 3 show the values of the pergolas with unequal beam spacing and with equal beam spacing, respectively, in which *n* represents the number of the beams.

In order to get the luminance ratio of the bright area to the dark area, which was expressed in terms of *x*, the luminance of the bright area and the dark area was measured. At 10:00, the luminance of the bright area was about 1600–1800 cd/m^2, and the luminance of the dark area was about 150–250 cd/m^2. At 12:00, the luminance was 2600–3000 cd/m^2 and 200–280 cd/m^2, respectively. At 14:00, the luminance was 2800–3200 cd/m^2 and 250–300 cd/m^2 respectively. It could be concluded that the luminance of the bright area was about 10 times that of the dark area, so the ratio *x* was evaluated at 10.

4.2. Calculation with unequal beam spacing

The parameters needed to calculate the UGR are shown in Table 4. The luminance of the light area (L_a) was 3000 cd/m^2, which was the biggest value at 12:00, and the UGR was calculated to be 19 according to Eq. (7).

The UGR values of common rooms or places in public buildings and industrial buildings are clearly stipulated in *the standard for lighting design of buildings*, most of which do not exceed 22 (China Academy of Architectural Sciences, 2013). This limit is also adopted in the analysis of the discomfort glare of a tunnel pergola. As a result, 19 is smaller than 22, so that no discomfort glare will be generated when the driver drives through the pergola. However, if the luminance of the bright area reaches 7,000 cd/m^2, the UGR will be greater than 22, and discomfort glare will be generated.

4.3. Calculation with equal beam spacing

According to the length of the pergola, the amount of the beams, and the width of the beam, the equal beam spacing was calculated to be 1050 mm. The parameters needed are listed in Table 4. The UGR was calculated to be 19, which was also smaller than 22. Thus, there was no discomfort glare when the drivers drove through the pergola. However, if the luminance of the bright area reached 7000 cd/m^2, the UGR would be greater than 22, and the discomfort glare would be generated.

4.4. Contrast between the two pergolas

Table 5 shows parts of the UGR values for different luminance amounts of the bright area of the two kinds of pergolas. The values are

Table 2
P values of the pergola with unequal beam spacing.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
H (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
R (m)	10	12	14	16	18	19	21	23	24	25	27	28	29	30	31	31	32
H/R	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
T/R	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P	1.53	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.00	1.00	1.00

Table 3
P values of the pergola with equal beam spacing.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
H (m)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
R (m)	9	11	12	14	15	16	18	19	21	22	23	25	26	28	29	30	32
H/R	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0
T/R	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
P	1.53	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.00	1.00

Table 4
Values of Parameters.

	L_a (cd/m^2)	x	l (m)	a_i (mm)	b_i (mm)
Unequal beam spacing	3000	10	9	350	1800–300
Equal beam spacing	3000	10	9	350	1050

Table 5
Contrast of the UGR values for different luminance amounts.

L_a (cd/m^2)	2000	3000	4000	5000	6000	7000
Unequal beam spacing	18.06	19.46	20.46	21.24	21.87	22.41
Equal beam spacing	17.96	19.37	20.37	21.14	21.78	22.31

not listed as integers for easier comparison. It could be concluded that when the luminance of the bright area was the same, the UGR of the pergola with equal beam spacing was a little smaller than that with unequal beam spacing. When the UGR was equal to 22, that is, the limit of discomfort glare, higher luminance was needed for the pergola with equal beam spacing. This shows that the design of equal beam spacing was less uncomfortable than the design of unequal beam spacing.

5. Analysis of the discomfort glare

In view of the discomfort glare, because the performance of the pergola with equal beam spacing was nearly the same as the performance of the pergola with unequal beam spacing, when the basic parameters of the highway were determined, the pergola could be preliminarily designed by referring to the UGR with equal beam spacing. Furthermore, the pergola with unequal beam spacing could be designed using the same basic parameters, except for the beam spacing. Thus, the analysis was undertaken for the pergola with equal beam spacing.

5.1. Analysis for a fixed beam width and a fixed number of beams

It is a fact that the road width and the luminance ratio between the bright area and the dark area could be easily acquired, through either the basic parameters of road design or investigations. The two parameters could be considered as constant when calculating the UGR; the parameter values were 9 m and 10, and they were consistent with the basic parameters described above. The value of the position index P was taken according to the values of H/R and T/R. Then four parameters were unknown: The luminance of the bright area (L_a), the width ratio between the bright area and the dark area (y), the amount of the beams (n), and the width of the dark area when the sun was vertically shining (a), which was equal to the beam width (z). Then following equation could be obtained:

$$UGR = 8\lg(L_a \sum_{i=1}^{n} \frac{33.75ya}{P_i^2\left(2.25 + (8.5 + (y+1)ia - \frac{b_i}{2})^2\right)^{\frac{3}{2}}}) \tag{9}$$

Because this part analyzed the discomfort glare with a fixed beam width and a fixed number of beams, the values of which were 350 mm and 17, respectively, Eq. (10) could be obtained:

$$UGR = 8\lg(L_a \sum_{i=1}^{17} \frac{11.8125y}{P_i^2(2.25 + (8.5 + 0.35(y+1)i - 0.175y)^2)^{\frac{3}{2}}}) \tag{10}$$

There were only two parameters left to determine in order to calculate the UGR, which were L_a and y. In the calculation, L_a ranged from 11,000 to 3000 cd/m^2, at which value most of the glare could be caused, corresponding to the illuminance range 242,000–66,000 Lx, which was converted using the formula L = E/22 (Ministry of Transport of the People's Republic of China, 2004), in which L is the luminance, E is the illuminance, and y ranges from 1 to 3.

The results show that when L_a was bigger than 6500 cd/m^2 and y is bigger than 2.9, or when L_a was bigger than 7000 cd/m^2 and y was bigger than 2.4, or when L_a was bigger than 7500 cd/m^2 and y was bigger than 2.0, or when L_a was bigger than 8000 cd/m^2 and y was bigger than 1.7, or when L_a was bigger than 8500 cd/m^2 and y was bigger than 1.6, or when L_a was bigger than 9000 cd/m^2 and y was bigger than 1.5, or when L_a was bigger than 9500 cd/m^2 and y was bigger than 1.4, or when L_a was bigger than 10000 cd/m^2 and y is bigger than 1.1, or when L_a was bigger than 10,500 or 11,000 cd/m^2 and y was bigger than 1.1, the UGR was bigger than 22 and the discomfort glare appeared.

Fig. 4 shows the UGR variation diagram, in which the abscissa is the width ratio between the bright area and the dark area (y), and the ordinate is the UGR. The curves describe the changes of L_a from 11000 cd/m^2 to 3000 cd/m^2. It could be concluded that when the luminance was constant, the bigger y was, the bigger the UGR was and the worse the discomfort glare was. When y was determined, the bigger the luminance was, the bigger the UGR was and the worse the discomfort glare was. These findings were all in line with the intuitive feelings of most people towards discomfort glare. However, the increasing rate of UGR gradually decreased with the increase of y and L_a, indicating that when the discomfort glare reached a certain degree, the influence of L_a and y gradually weakened.

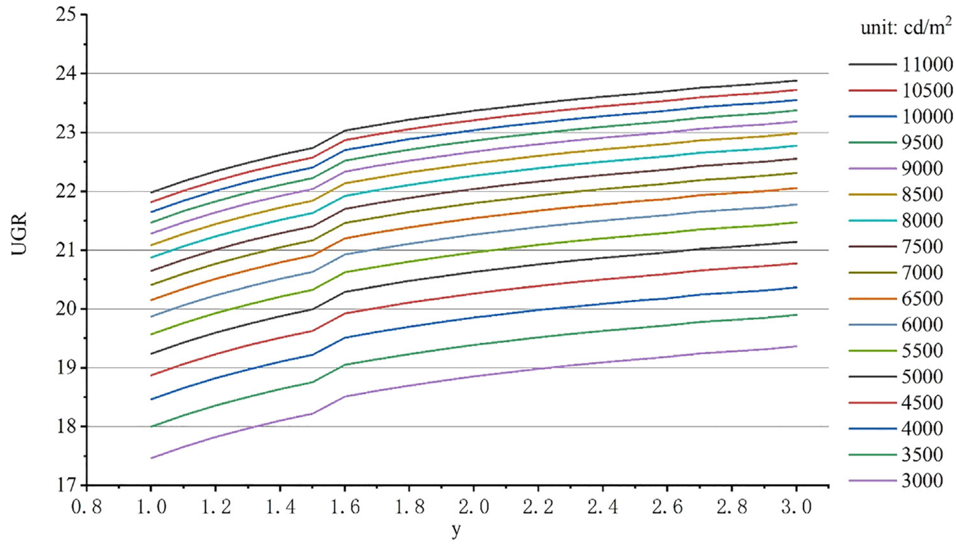

Fig. 4. UGR variation diagram.

5.2. Analysis for a fixed beam width and an unfixed number of beams

When the beam width was fixed at 350 mm and the amount of the beams was unfixed, ranging from 17 to 7, the range of y was obtained when the UGR was bigger than 22, as shown in Table 6. The space in the table indicates that the UGR would not be bigger than 22, and the discomfort glare would not be generated.

It could be concluded that if the amount of the beams was confirmed, when the luminance of the bright area was big, the UGR could reach 22 at a small beam spacing, and the beam spacing was inversely proportional to the luminance of the bright area. If the luminance of the bright area was confirmed, the beam spacing was also inversely proportional to the amount of beams.

5.3. Analysis for an unfixed beam width and a fixed number of beams

When the beam width was unfixed, ranging from 200 to 450 mm, and the amount of beams was fixed at 17, the range of y was obtained when the UGR is bigger than 22, as shown in Table 7. The spaces in the table indicate that the UGR would not be bigger than 22 and discomfort glare would not be generated.

It could be concluded that if the beam width was confirmed, when the luminance of the bright area was big, the UGR could reach 22 at a small beam spacing, and the beam spacing was inversely proportional to the luminance of the bright area. If the luminance of the bright area was confirmed, the beam spacing was also inversely proportional to the beam width.

5.4. Design of a pergola based on discomfort glare

The UGR of the pergola with equal beam spacing was almost the same as the UGR of the pergola with unequal beam spacing, while the other parameters were the same. Hence, the pergola could be preliminarily designed with equal beam spacing, and then the pergola with unequal beam spacing could be designed using the same basic parameters, except for the beam spacing.

In the design of a pergola with equal beam spacing, taking the discomfort glare into account, the UGR should be calculated first using different parameters besides the basic parameters of the highway, including the width ratio between the bright area and the dark area (y), the amount of the beams (n), and the beam width (a). The UGR should be compared with different parameters, and a cost-optimal design method should be chosen. It should be noted that the discomfort glare is just one factor in the design. Other factors should also be considered such as the disability glare, the flickering effect, and so on.

6. Conclusion

The pergola at the portal of a tunnel, which can provide an area of light transition during the day, is very important for driving safety and preventing a disabled glare. However, when the sun shines directly on a pergola, there are bright and dark areas on the ground, which can cause

Table 6
Range of y where the UGR > 22.

y	La (cd/m^2)									
	> 11000	> 10500	> 10000	> 9500	> 9000	> 8500	> 8000	> 7500	> 7000	> 6500
17	> 1.1	> 1.1	> 1.2	> 1.4	> 1.5	> 1.6	> 1.7	> 2.0	> 2.4	> 2.9
16	> 1.1	> 1.2	> 1.3	> 1.4	> 1.6	> 1.6	> 1.8	> 2.0	> 2.4	> 3.0
15	> 1.1	> 1.2	> 1.3	> 1.5	> 1.6	> 1.6	> 1.8	> 2.1	> 2.5	
14	> 1.2	> 1.3	> 1.4	> 1.5	> 1.6	> 1.7	> 1.9	> 2.2	> 2.6	
13	> 1.2	> 1.3	> 1.4	> 1.6	> 1.6	> 1.7	> 2.0	> 2.3	> 2.7	
12	> 1.3	> 1.4	> 1.5	> 1.6	> 1.6	> 1.8	> 2.1	> 2.4	> 2.8	
11	> 1.3	> 1.4	> 1.6	> 1.6	> 1.7	> 1.9	> 2.2	> 2.5	> 3.0	
10	> 1.4	> 1.5	> 1.6	> 1.6	> 1.8	> 2.0	> 2.3	> 2.7		
9	> 1.5	> 1.6	> 1.6	> 1.8	> 1.9	> 2.2	> 2.5	> 2.8		
8	> 1.6	> 1.6	> 1.7	> 1.9	> 2.1	> 2.3	> 2.7			
7	> 1.6	> 1.8	> 1.9	> 2.1	> 2.3	> 2.6	> 2.9			

Note: The spaces indicate that the UGR would not be bigger than 22.

Table 7
Range of y where the UGR > 22.

z (mm)	La (cd/m^2)									
	> 11000	> 10500	> 10000	> 9500	> 9000	> 8500	> 8000	> 7500	> 7000	> 6500
200	> 1.4	> 1.5	> 1.6	> 1.8	> 1.9	> 2.0	> 2.3	> 2.6		
250	> 1.2	> 1.3	> 1.4	> 1.5	> 1.7	> 1.8	> 2.1	> 2.5	> 2.7	
300	> 1.1	> 1.2	> 1.3	> 1.4	> 1.6	> 1.8	> 2.0	> 2.1	> 2.4	> 3.0
350	> 1.1	> 1.1	> 1.2	> 1.4	> 1.5	> 1.6	> 1.7	> 2.0	> 2.4	> 2.9
400	> 1.0	> 1.1	> 1.2	> 1.2	> 1.3	> 1.5	> 1.7	> 2.0	> 2.3	> 2.9
450	> 1.0	> 1.0	> 1.1	> 1.2	> 1.3	> 1.5	> 1.7	> 1.9	> 2.3	> 2.8

Note: The spaces indicate that the UGR would not be bigger than 22.

a discomfort glare for drivers. In order to quantitatively evaluate the level of discomfort glare, the UGR, which is used to evaluate the glare level in lighting places, was innovatively used in this research. Additionally, the bright areas were treated as lamps and the dark areas were treated as dark backgrounds. Finally, the formulas for calculating the level of the discomfort glare were derived, including the formulas for pergolas with equal beam spacing and unequal beam spacing. After calculating the UGR with the specific parameter values according to the formulas, it could be concluded that the pergolas with equal beam spacing were almost the same as the pergolas with equal beam spacing with respect to reducing the discomfort glare.

The changing rule of the discomfort glare was analyzed under different changes of the parameters, namely the analysis for the fixed beam width and the fixed number of beams, the analysis for the fixed beam width and the unfixed number of beams, and the analysis for the unfixed beam width and the fixed number of beams. In order to design a pergola that can both meet the requirement of avoiding the discomfort glare and be cost optimal, different UGRs should be compared using the analysis methods mentioned above. The UGR of a pergola with equal beam spacing is much easier to calculate than that of a pergola with unequal beam spacing. Therefore, the former structure should be designed first; then the latter one can be designed using the same parameters, except for the beam spacing. The results of this research offer a better choice for a pergola, which can make it provide more comfort other than the disability glare, the flickering effect, and so on; these are all important to driving safety.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tust.2019.103161.

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