Hindawi
Advances in Materials Science and Engineering
Volume 2022, Article ID 2376813, 13 pages
https://doi.org/10.1155/2022/2376813

Research Article

Evaluation of the Effects of Tunnel Lighting Environment on Energy Consumption and Drivers' Reaction Time

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Received 15 May 2022; Accepted 7 June 2022; Published 17 June 2022

Academic Editor: Xiaolong Sun

The 24-hour artificial lighting of the tunnels consumes a large amount of electricity, which means increased environmental damage and carbon footprint for China, which is dominated by thermal power. In order to alleviate the above problems, the effects of the tunnel lighting environment on energy consumption and drivers' reaction time were evaluated by the finite element method and laboratory test to optimize the lighting environments. In this study, based on the Wanxichong extra-long tunnel in Yunnan Province, a 3D tunnel model using DIALux software is established first. Then, the effects of climate conditions, layout method of the lamps, and layout height and reflection of the sidewall material on the average luminance and uniformity on the pavement, the efficiency ratio per unit length, and the actual energy efficiency value were investigated. Finally, the indoor lighting environment simulation experiments were conducted to examine the effect of the type of sidewall materials, contrast, background luminance, and eccentricity on drivers' reaction time. Simulation results show that, under the same climate condition and layout method of lamps, the average luminance and luminance uniformity on the road surface are positively correlated with the reflectivity of the sidewall material. On the clear days, the efficiency ratio per unit length corresponding to the 2 m high sidewall material is the largest, while the efficiency ratio per unit length on cloudy days and mixed days corresponding to the 2.5 m high sidewall material is the largest. In addition, the staggered layout of the lamps at the entrance of the tunnel consumes less power, which is more conducive to energy saving. Experimental results show that, with the increase of background luminance, the reaction time of drivers decreases. Meanwhile, applying energy-storage reflective coating on the sidewalls of the tunnel has a better visual performance than using light yellow ceramic tiles and cement mortar on the sidewalls. This conclusion would provide a lower energy consumption lighting design method and higher drive comfortable for highway tunnels.

1. Introduction

The sustainable development of infrastructure is an important development goal in the future [1–4]. With the development of China's transportation industry, the mileage of tunnels in China has increased rapidly [5–7]. Compared with the open road, the tunnel is a semiclosed tubular structure, resulting in a great difference in luminance inside and outside the tunnel. According to the Rules of Highway Tunnel Lighting Design (JTG/T D70/2-01-2014), the tunnel should be installed in the lighting facilities when the length of the tunnel is higher than 100 m. Therefore, due to the closed characteristics of the tunnel, the tunnel needs to provide a 24-hour artificial light source to ensure driving safety in the tunnel [8–10]. For this reason, the tunnel lighting system will bear overloading energy consumption and management costs. This means increased environmental damage and carbon footprint for China, which is dominated by thermal power. In addition, although lighting is installed inside the tunnel to reduce the luminance difference, the luminance difference between inside and outside of the tunnel is still largely due to the excessive natural light outside the tunnel. As a result, unique visual phenomena, such as "black hole" and "white hole," still appear in the tunnel entrance and exit section [11–15]. Therefore, it is necessary to optimize the luminance and energy consumption of the tunnel from the perspective of environmental sustainability.

In order to better solve the above phenomenon in tunnels, researchers have carried out a lot of research on the luminance at the tunnel entrance [16–18]. Guo et al. studied the relationship between the external environment surrounding the tunnel entrance and the driving behavior, and they concluded that driving safety would be influenced by the luminance at the entrance and exit of the tunnel. In this case, they proposed a safety design plan for the tunnel based on the vehicle speed [19]. Angel Pachamanov and Dessislava Pachamanova proposed an optimization method to design the lighting distribution of luminaries for tunnels based on the International Commission on Luminance, and they found that the optimization model can significantly improve the lighting parameters of luminaries, thus resulting in the lowest energy consumption for lighting installations [20]. Liu et al. investigated the effect of light source color on tunnel lighting based on the experiment of reaction times, and they concluded that the appropriate light sources in different sections of tunnel lighting were selected in terms of the influence of light source color on visual performance [21]. Xie et al. used the DIALux software to compare the average luminance of different lamps forms and spacing, and they found that the luminance of staggered sides arraignment of the lamp is the highest when the layout spacing of lamps was the same, while the luminance of the lamps with centerline sideways is the worst [22]. Na et al. explored the effects of the different combinations of lighting power and the installation space on surface luminance and uniformity on the road, and they concluded that when the power is small and the installation space is large, the surface luminance becomes smaller, but uniformity is better [23]. Zhang et al. optimized the lighting environment at the entrance of highway tunnels by using the simulation method and found that the change of natural luminance is the strongest within 5 m from the tunnel entrance, while when the distance is larger than 5 m, the change of natural luminance decreases significantly [24]. Yang et al. investigated the effect of white LED and high-pressure sodium lamp on the reaction time of drivers under different background luminance, and they concluded that the white LED can provide a shorter reaction time for drivers [25]. Cai et al. studied the optimal values of contrast revealing coefficient under different lighting systems, and they found that the optimal value under symmetric lighting was 0.2 and the optimal value under counter-beam lighting was 0.85 [26].

In summary, the tunnel lighting environment design, including climate condition, sidewall, pavement, and the layout of the lamp and vault, is different from the road lighting and has obvious particularity and importance. On the one hand, the energy efficiency of artificial light sources and the luminance and luminance uniformity on the pavement are influenced by the lighting environment. On the other hand, the drivers' reaction time also has a close relationship with the lighting environment. In this case, to investigate and optimize the complex and changeable lighting environment in the tunnel, based on the Wanxichong extra-long tunnel in Yunnan Province, the simulation and experimental research will be conducted at the entrance section, middle section, and exit section of the tunnel. Firstly, a 3D tunnel model using DIALux software is established. The 30 m long pavement surface with both sides inside the tunnel is set as the measurement area, and the effects of different climate conditions, layout methods of lamps, and the reflectivity of sidewall materials on the tunnel lighting quality and energy-saving effect at the entrance and exit are investigated. Based on the simulation results, the optimal lighting parameters at the entrance and exit of the tunnel with the different conditions will be discussed. Finally, the indoor lighting environment simulation system of the highway tunnel is established, and the test parameters such as type of sidewall materials, contrast, background luminance, and eccentricity are selected to investigate the reaction time of the participants.

(1) 3D model of tunnel (2) Schematic of cross section of tunnel

Figure 1: The three-dimensional simulation model of the tunnel: (a) 3D model of tunnel and (b) schematic of cross section of tunnel.

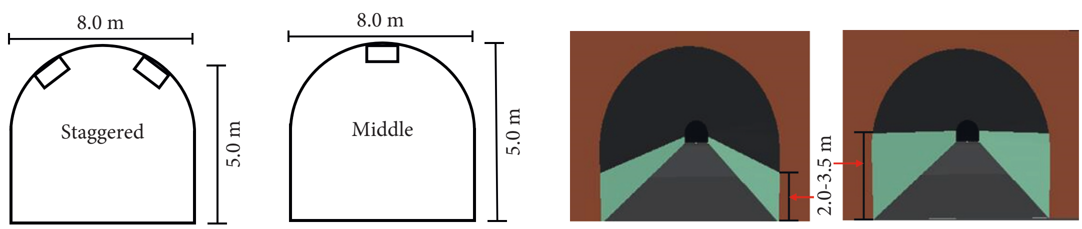
2. Simulation Research

2.1. 3D Model Establishment of the Tunnel. The purpose of the lighting simulation is to optimize the lighting conditions at the entrance of the Wanxichong extra-long tunnel in Yunnan. The DIALux simulation software was selected to carry out a 3D simulation analysis of the tunnel with different climate conditions (clear, cloudy, and mixed) combined with lamps and reflections from the inner wall of the tunnel. The actual tunnel geometry at the tunnel entrance is complex, and it is difficult to directly establish a tunnel model using the space module of the DIALux software. However, the tunnel can be disassembled according to its geometric size. As shown in Figure 1, the cross section of the three-dimensional simulation model of the tunnel can be composed of a circular arch and multiple cubes. The length, width, and height of the tunnel model are 200 m, 8 m, and 6.75 m, respectively. In addition, according to the characteristics of the tunnel sidewalls in Chongqing, the geometric dimensions of the bottom of the model were divided into three heights from bottom to top during the model building process, which were 2 m, 0.5 m, and 0.5 m, respectively. In this case, the reflectivity of the inner side material at different heights can be adjusted.

Compared with the open section of the road, the tunnel is a semiclosed tubular structure, resulting in a great difference in luminance inside and outside the tunnel. Although a lamp is installed inside the tunnel to reduce the luminance difference, due to the excessive natural light outside the tunnel and the requirement of energy saving in tunnel operation, the luminance difference between inside and outside of the tunnel is still large. As a result, unique

Table 1: The layout parameters of the lamps.

Type	Spacing	Height	Installed angle
Staggered lighting	1.5	5	30°
Middle lighting	0.75	6.75	90°



(1) Schematic of lamp layout (2) Schematic of layout height of reflective materials of the side walls

Figure 2: The schematic of lamp layout and layout height of reflective materials of the sidewall. (a) Schematic of lamp layout. (b) Schematic of layout height of reflective materials of the sidewall.

visual phenomena such as "black holes" and "white holes" will appear in the tunnel entrance and exit section. Therefore, in this simulation, the 30 m long road surface with the opening on both sides of the tunnel is set as the measurement area, and the luminance on the road surface under different working conditions is calculated. The entrance is the southward tunnel, and the exit is the northward tunnel.

2.2. Scheme Design of the Simulation. The luminance at the entrance of the tunnel is affected by many factors, such as the natural light outside the tunnel, the light source of lamps in the tunnel, and the materials of the sidewall. Therefore, in this section, these above factors will be considered in the 3D simulation analysis of the tunnel, including the different climate conditions (clear, cloudy, and mixed days), layout arrangement of lamps, and reflectivity of the material of the sidewall of the tunnel.

2.2.1. Climate Conditions. The Wanxichong extra-long tunnel is located in the northern hemisphere. On December 22 of each year, the sun shines directly on the tropic of Capricorn, and the northern hemisphere gets the least amount of sunlight at this time. Therefore, in this study, the different climate conditions (clear, cloudy, and mixed days) were considered. The noon with the highest sunlight intensity and the smallest sun elevation angle on December 22 is selected as the natural light environment for simulation analysis. At this moment, the sunlight can directly enter the entrance of the southward tunnel on clear days. In addition, there is little direct sunlight at the entrance of the southward tunnel and exit of the northward tunnel when the climate condition is cloudy and mixed days.

2.2.2. Layout Method of the Lamps. In this study, the LED lights for tunnels with a color temperature of 4500 K and a power of 160 W produced by Yaming Company, Shanghai, were selected. The layout of the lamps has a great influence on the lighting quality of the tunnel. For the same type and quantity of lamps, the average luminance and uniformity on the road surface in the tunnel will vary greatly due to the layout method of the lamps. When the average luminance on the road surface is large and the uniformity is low, the zebra effect is likely to occur, which endangers driving safety. In this case, this study intends to adopt two common layouts of lamps in tunnels: double-sided staggered lighting and middle lighting. The detailed layout methods of the lamps are shown in Table 1 and Figure 2(a).

2.2.3. Layout Height and Reflectivity of the Sidewall Material. The inner sidewall material of the tunnel has a reflective synergistic effect on the luminance on the road surface in the tunnel, and the greater the reflectivity, the better the material's reflection performance. Therefore, in order to investigate the effects of reflectivity on the luminance quality, the reflection coefficients of the inner sidewall material were taken as 0.75, 0.80, and 0.85. In addition, the sidewall without sidewall materials and vault shall be sprayed with a dark gray fire-retardant coating with a reflectivity of 0.1. The asphalt pavement was selected as the surface material of the road in the tunnel, and the reflection coefficient was taken as 0.2. Based on the actual situation of the tunnel, 2 m, 2.5 m, 3 m, and 3.5 m are, respectively, taken as the layout heights of the sidewall materials, as shown in Figure 2.

In summary, with the climate conditions (clear, cloudy, and mixed days), the reflectivity (0.75, 0.80, and 0.85) of the sidewall material, the layout height of lamps (2 m, 2.5 m, 3 m, and 3.5 m), the layout method of lamps (staggered and middle) as the independent variables, and the average luminance, uniformity, and energy efficiency value as the dependent variables, the lighting at the entrance and exit of the tunnel is optimized. Combined with these above factors, the simulation schemes of the 3D model of the tunnel are shown in Table 2.

3. Experimental Research

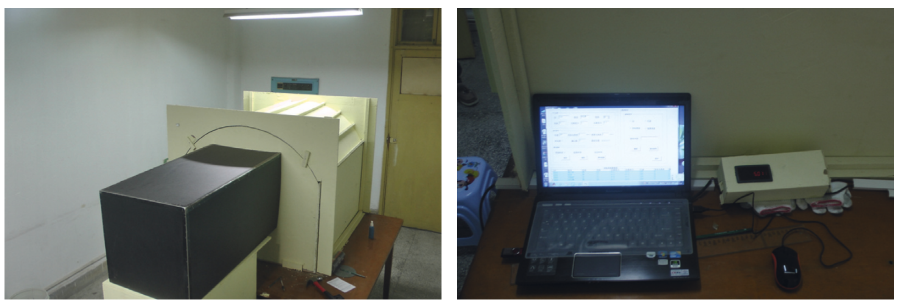
The lighting luminance in the tunnel will have an impact on the driver's reaction time. According to the calculation formula of the stopping sight distance, the length of the

Table 2: The simulation schemes of the 3D model of the tunnel.

No.	Reflectivity of sidewall	Climate condition	Layout method	Layout height of sidewall (m)
1	0.75	Clear	Staggered	2
2	0.75	Clear	Staggered	2.5
3	0.75	Clear	Staggered	3
4	0.75	Clear	Staggered	3.5
5	0.75	Clear	Middle	2
6	0.75	Clear	Middle	2.5
7	0.75	Clear	Middle	3
8	0.75	Clear	Middle	3.5
9	0.75	Cloudy	Staggered	2
10	0.75	Cloudy	Staggered	2.5
11	0.75	Cloudy	Staggered	3
12	0.75	Cloudy	Staggered	3.5
13	0.75	Cloudy	Middle	2
14	0.75	Cloudy	Middle	2.5
15	0.75	Cloudy	Middle	3
16	0.75	Cloudy	Middle	3.5
17	0.75	Mixed	Staggered	2
18	0.75	Mixed	Staggered	2.5
19	0.75	Mixed	Staggered	3
20	0.75	Mixed	Staggered	3.5
21	0.75	Mixed	Middle	2
22	0.75	Mixed	Middle	2.5
23	0.75	Mixed	Middle	3
24	0.75	Mixed	Middle	3.5
25	0.8	Clear	Staggered	2
26	0.8	Clear	Staggered	2.5
27	0.8	Clear	Staggered	3
28	0.8	Clear	Staggered	3.5
29	0.8	Clear	Middle	2
30	0.8	Clear	Middle	2.5
31	0.8	Clear	Middle	3
32	0.8	Clear	Middle	3.5
33	0.8	Cloudy	Staggered	2
34	0.8	Cloudy	Staggered	2.5
35	0.8	Cloudy	Staggered	3
36	0.8	Cloudy	Staggered	3.5
37	0.8	Cloudy	Middle	2
38	0.8	Cloudy	Middle	2.5
39	0.8	Cloudy	Middle	3
40	0.8	Cloudy	Middle	3.5
41	0.8	Mixed	Staggered	2
42	0.8	Mixed	Staggered	2.5
43	0.8	Mixed	Staggered	3
44	0.8	Mixed	Staggered	3.5
45	0.8	Mixed	Middle	2
46	0.8	Mixed	Middle	2.5
47	0.8	Mixed	Middle	3
48	0.85	Mixed	Middle	3.5
49	0.85	Clear	Staggered	2
50	0.85	Clear	Staggered	2.5
51	0.85	Clear	Staggered	3
52	0.85	Clear	Staggered	3.5
53	0.85	Clear	Middle	2
54	0.85	Clear	Middle	2.5
55	0.85	Clear	Middle	3
56	0.85	Clear	Middle	3.5
57	0.85	Cloudy	Staggered	2
58	0.85	Cloudy	Staggered	2.5
59	0.85	Cloudy	Staggered	3
60	0.85	Cloudy	Staggered	3.5

Table 2: Continued.

No.	Reflectivity of sidewall	Climate condition	Layout method	Layout height of sidewall (m)
61	0.85	Cloudy	Middle	2
62	0.85	Cloudy	Middle	2.5
63	0.85	Cloudy	Middle	3
64	0.85	Cloudy	Middle	3.5
65	0.85	Mixed	Staggered	2
66	0.85	Mixed	Staggered	2.5
67	0.85	Mixed	Staggered	3
68	0.85	Mixed	Staggered	3.5
69	0.85	Mixed	Middle	2
70	0.85	Mixed	Middle	2.5
71	0.85	Mixed	Middle	3
72	0.85	Mixed	Middle	3.5



(1) lighting environment system of the highway tunnel

(2) Data acquisition

Figure 3: The lighting environment system and data acquisition. (a) Lightning environment system of highway tunnel. (b) Data acquisition.

reaction time has a direct impact on the stopping sight distance. Therefore, the value of the lighting luminance in the tunnel will indirectly affect the stopping sight distance in the tunnel. In this study, the purpose of the experiments is to measure the reaction time of the participants to observe small objects under different luminance levels by simulating the lighting environment system of the highway tunnel.

The lighting environment simulation system of a highway tunnel consists of three parts: observation box, optical system, and light box, as shown in Figure 3. The ratio of the simulated device to the actual tunnel size is 1 : 10. The width of the pavement inside the tunnel is 1 m, the height of the sidewall is 0.6 m, and the vault is made of a 1/3 circle with an approximate diameter of 0.57 m. The entire observation box is made of the wood skeleton and filled with plywood. The current mainstream light source (80W LED light) was selected, and its luminance range (1–15 cd/m2) can be adjusted to simulate the luminance level of the middle section of the tunnel. A random light spot is used to simulate the obstacles that may appear when driving through the tunnel. The diameter of the light spot is 25 mm, which can completely fall in the fovea of the participants' eyes. The luminance of the light spot and the luminance of the background are provided by the same light source to ensure that their luminance has the same spectral distribution. In addition, the luminance of the light spot can be adjusted arbitrarily to form a different contrast with the background. Reaction time refers to the time difference between the light spot appearing and the participants pressing the button under each test condition.

To investigate the reaction time of the participants, the test parameters such as type of sidewall materials, contrast, background luminance, and eccentricity were selected for the experiments, as shown in Table 3. In this experiment, three kinds of sidewall materials were selected, including cement mortar, light yellow ceramic tile, and energy-storage reflective coating. These kinds of background luminance, including 2 cd/m2, 6 cd/m2, and 10 cd/m2, were used. Three kinds of eccentricity were selected, including 0°, 10°, and 20°. In addition, two kinds of contrast (0.2 and 0.5) were used. Ten people were selected as test subjects, and their ages ranged from 24 to 30 years. All participants had normal color vision and corrected visual acuity. In addition, all participants understood the purpose of the experiments. Test procedures were as follows:

(1) Before starting each group of experiments, a luminance meter was used to calibrate the luminance of the background and light spot of the two-contrast ratio. All participants spent 30 minutes to adapt to the darker experimental environment. Both eyes of the participants were used to observe the objects during the experiment, and they needed to ensure that both eyes were always looking at the cross mark in front of them.

(2) The observer holds the reaction time trigger button for testing and records the reaction time. If the subject does not respond or the reaction time exceeds a certain interval when the light spot appears, it will be regarded as invalid data.

Table 3: Value of the test parameters.

Test parameters	Value		
Sidewall materials	Cement mortar	Light yellow ceramic tile	Energy-storage reflective coating
Contrast (C)	0.2		0.4
Background luminance	2	6	10
Eccentricity (θ)	0°	10°	20°

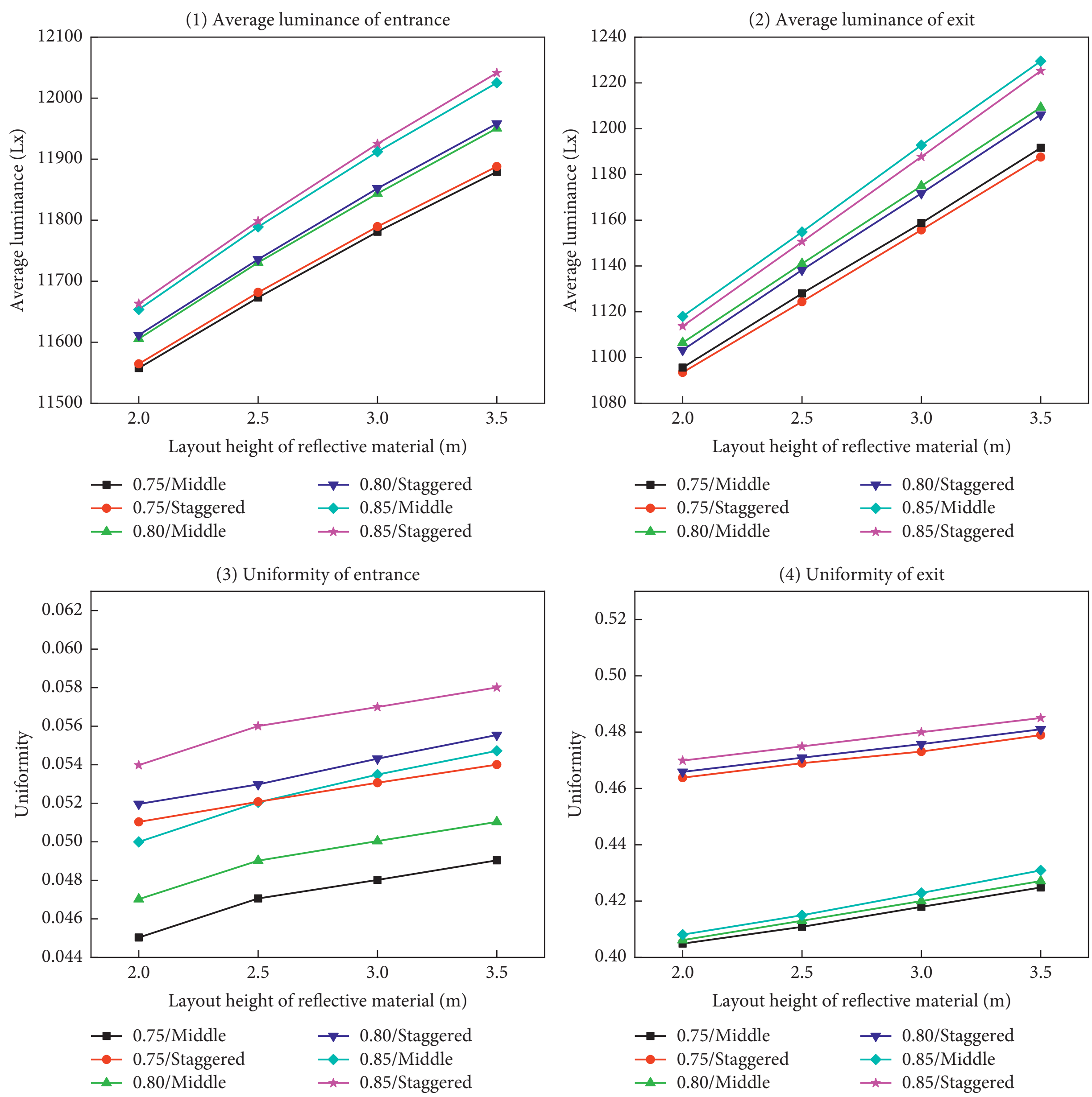


Figure 4: The average luminance and uniformity on the road surface on the clear days. (a) Average luminance of entrance. (b) Average luminance of exit. (c) Uniformity of entrance. (d) Uniformity of exit.

(3) The tests are performed in order of sidewall material type. Namely, after testing all the experimental schemes of a certain sidewall material, the experiment of the next material is conducted. In addition, in order to ensure the mental state of the participants, the duration of each experiment should not exceed two hours.

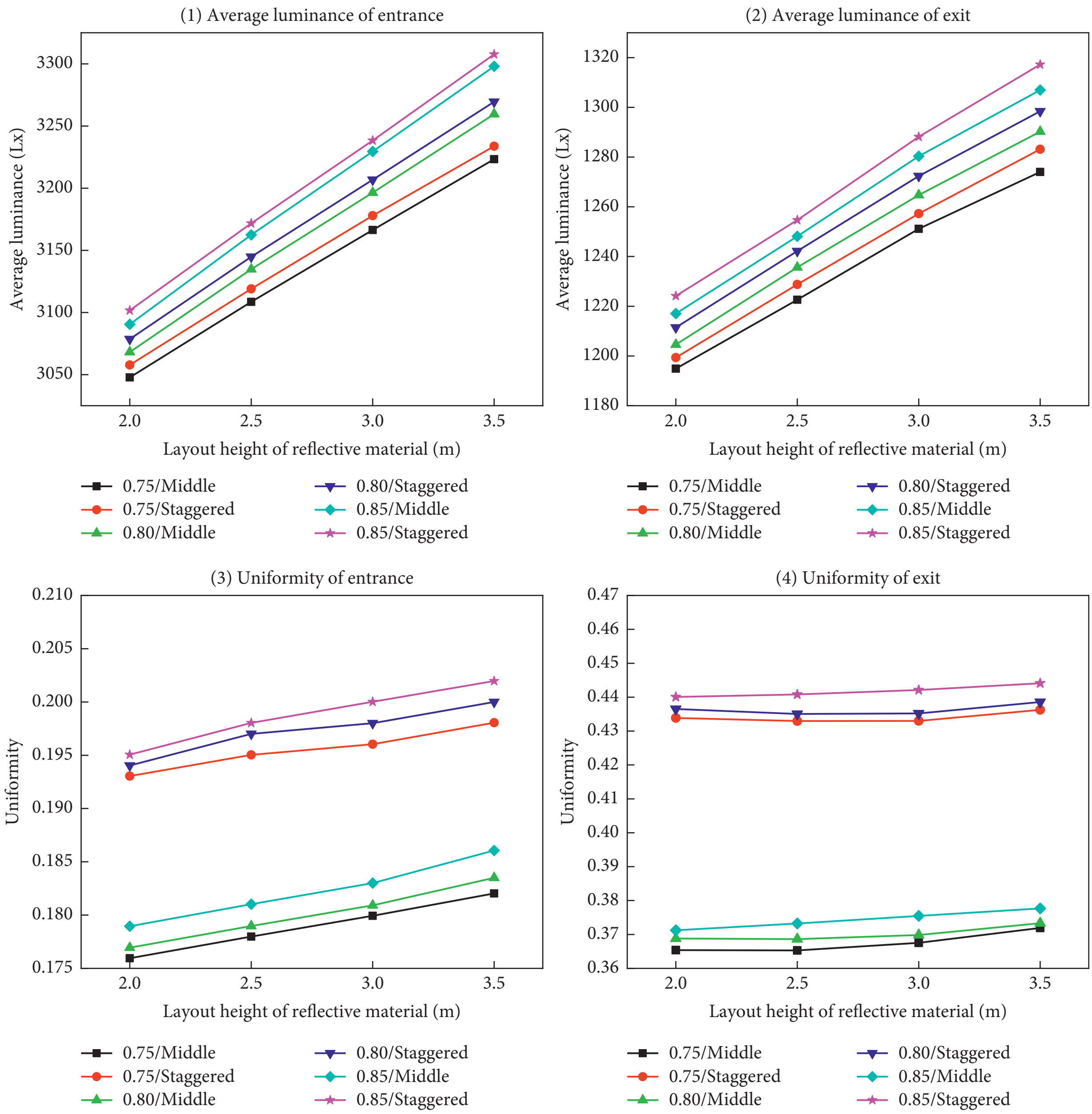


Figure 5: The average luminance and uniformity on the road surface on cloudy days. (a) Average luminance of entrance. (b) Average luminance of exit. (c) Uniformity of entrance. (d) Uniformity of exit.

(4) Finally, the reaction times of each participant were obtained under different conditions through the procedures of the experiment. The mean reaction time of the 10 participants was calculated.

4. Results and Discussion

4.1. Simulation Results and Discussion

4.1.1. Effect of Climate Condition on Average Luminance and Uniformity. The average luminance and luminance uniformity at the entrance and exit of the tunnel on clear days are shown in Figure 4. It can be seen that inner sidewall materials with high reflectivity at the entrance and exit sections of the tunnel can improve the average luminance on the road surface. When the layout method of lamps and the layout height of sidewall material is the same, as the reflectivity of the sidewall material increases from 0.75 to 0.85, the average luminance on the road surface at the entrance of the tunnel increases by 99 lx, 117 lx, 136 lx, and 149 lx, while the average luminance at the exit of the tunnel increases by 20 lx, 26 lx, 32 lx, and 36 lx. In addition, the sidewall material with high reflectivity is also beneficial in improving the luminance uniformity on the road surface. Another interesting phenomenon is that the average luminance at the entrance is larger, but the luminance uniformity is lower than that at the tunnel exit. This is because the entrance of the southward tunnel is directly irradiated by sunlight, which makes the

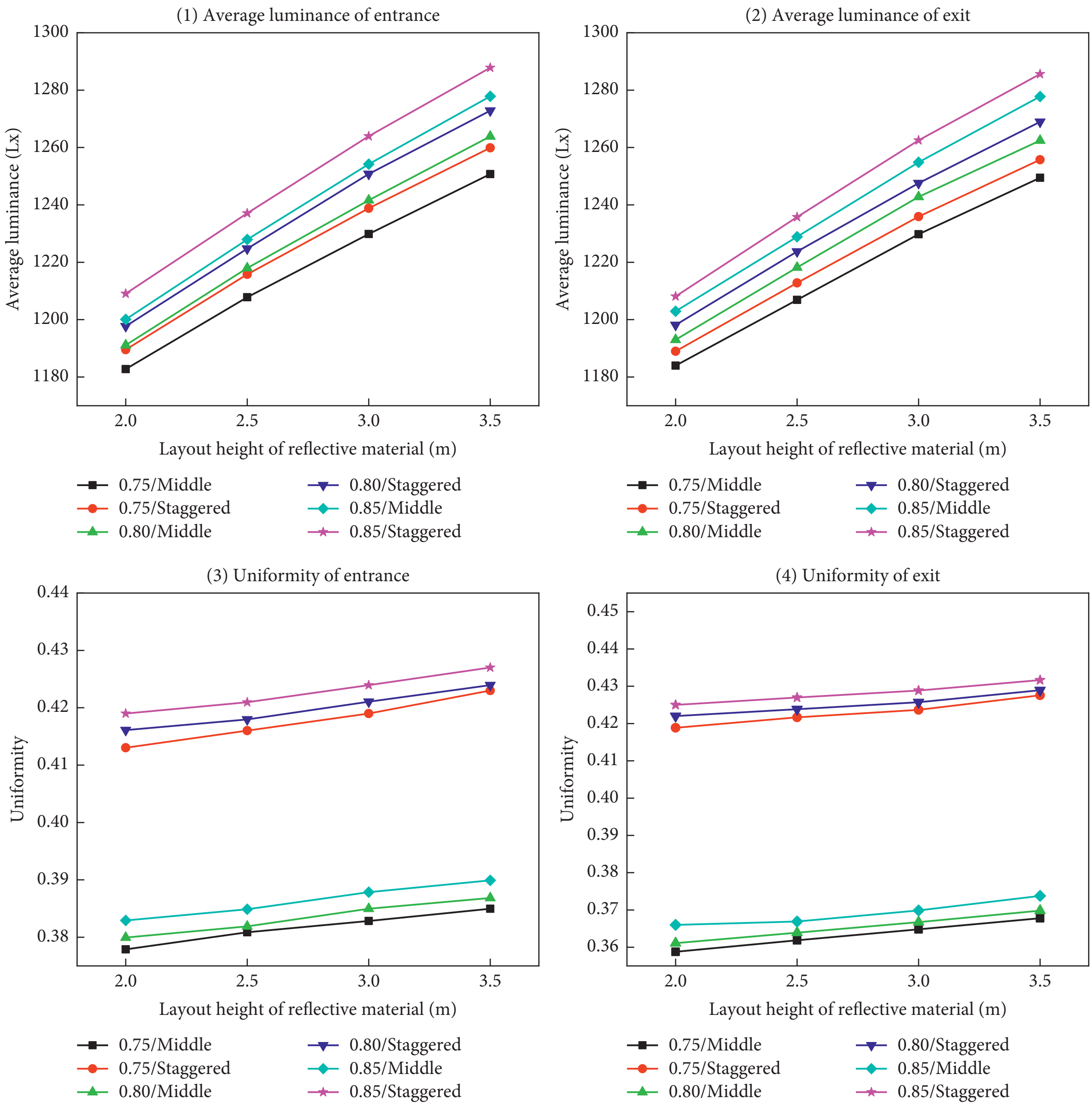


FIGURE 6: The average luminance and uniformity on the road surface on mixed days. (a) Average luminance of entrance. (b) Average luminance of exit. (c) Uniformity of entrance. (d) Uniformity of exit.

luminance distribution of the southward tunnel entrance extremely uneven, which seriously affects the driver's ability to distinguish the front target. Therefore, the arrangement of high-reflectivity sidewall materials at the tunnel entrance is a measure to improve the luminance uniformity, which is conducive to safe driving.

In addition, it can be observed that, on cloudy days, the average luminance and luminance uniformity at the exit and entrance of the tunnel are similar, as shown in Figure 5. When the layout method of lamps and the layout height of sidewall material are the same, as the reflectivity of the sidewall material increases from 0.75 to 0.85, the average luminance on the road surface at the entrance of the tunnel increases by 18 lx, 20 lx, 25 lx, and 28 lx. Also, the luminance conditions of the mixed days are similar to those of clear days, as shown in Figure 6. Namely, the average luminance on the road at the entrance to the south is higher than that of the entrance to the north, while the luminance uniformity at the entrance to the south is relatively low compared with the exit to the north. When the layout method of lamps and the layout height of sidewall material are the same, as the reflectivity of the sidewall material increases from 0.75 to 0.85, the average luminance on the road surface at the entrance of the tunnel increases by 44 lx, 53 lx, 63 lx, and 75 lx, while the average luminance at the exit of the tunnel increases by 22 lx, 25 lx, 31 lx, and 35 lx. The uniformity at the entrance and exit of the tunnel increases with the reflectivity of the sidewall material, but the improvement at

Table 4: Efficiency ratio per unit length of sidewall material at tunnel entrance.

Climate condition	Reflectivity	Layout height			
		2	2.5	3	3.5
Clear days	0.75	2.72%	2.58%	2.48%	2.37%
	0.80	2.94%	2.81%	2.67%	2.58%
	0.85	3.15%	3.04%	2.91%	2.78%
Cloudy days	0.75	4.35%	4.64%	4.59%	4.55%
	0.80	5.06%	5.22%	5.07%	4.76%
	0.85	5.07%	5.28%	5.21%	4.97%
Mixed days	0.75	5.22%	5.24%	4.92%	4.79%
	0.80	5.47%	5.51%	5.30%	5.19%
	0.85	5.87%	5.92%	5.68%	5.60%

Table 5: Efficiency ratio per unit length of sidewall material at tunnel exit.

Climate condition	Reflectivity	Layout height			
		2	2.5 (%)	3	3.5 (%)
Clear days	0.75	7.35%	7.21	7.10%	7.03
	0.80	7.41%	7.28	7.65%	7.49
	0.85	8.20%	7.87	8.25%	7.96
Cloudy days	0.75	5.15%	4.71	4.90%	5.04
	0.80	5.88%	5.29	5.39%	5.46
	0.85	6.62%	5.88	5.85%	5.90
Mixed days	0.75	5.07%	5.22	5.31%	4.97
	0.80	5.80%	5.80	6.28%	5.79
	0.85	6.52%	6.38	6.76%	6.21

the exit is relatively small. Therefore, the sidewall material with high reflectivity can improve the average luminance and luminance uniformity on the road at the entrance and exit when the climate condition is mixed days.

4.1.2. Effect of Layout Height of Sidewall Material on Efficiency Ratio per Unit Length. The layout height of the sidewall material has a significant impact on the improvement of the luminance of the road surface, thus affecting its energy-saving effect. In order to get the optimal layout height, the efficiency ratio per unit length was used as the evaluation index. This evaluation index is to first calculate the percentage of luminance improvement caused by the arrangement of sidewall materials with different heights in the tunnel relative to the whole sidewall sprayed with gray fire-retardant coating and then divide the above percentage by the height of the sidewall material under the corresponding working conditions to obtain the efficiency ratio per unit length.

The efficiency ratio per unit length with different layout heights of sidewall material is shown in Tables 4 and 5. According to the data in the table, the efficiency ratio per unit length at the tunnel entrance under different climate conditions is compared. It can be seen that, on the clear days, the efficiency ratio per unit length corresponding to the 2 m high sidewall material at the tunnel entrance is the largest. When the reflectivity of the sidewall material is 0.75, 0.80, and 0.85, the efficiency ratio per unit length is 2.72%, 2.94%, and 3.15%, respectively. On the cloudy days and mixed days, the efficiency ratio per unit length corresponding to the 2.5 m high sidewall material at the tunnel entrance is the largest. When the reflectivity of the sidewall material is 0.75, 0.80, and 0.85, the unit length efficiency ratios for cloudy days are 4.64%, 5.22%, and 5.28%, respectively, and as the reflectivity increases, the unit length efficiency ratio for mixed days also increases from 5.24% to 5.92%.

The efficiency ratio per unit length at the tunnel exit under different climate conditions is compared. It can be observed that, on clear days, the efficiency ratio per unit length corresponding to the 2 m high sidewall material at the tunnel exit is the largest when the reflectivity of the sidewall material is 0.75. However, the efficiency ratio per unit length corresponding to the 3 m high sidewall material at the tunnel exit is the largest when the reflectivity of the sidewall material is 0.80 and 0.85. On cloudy days, the efficiency ratio per unit length corresponding to the 2 m high sidewall material at the tunnel exit is the largest. When the reflectivity of the sidewall material is 0.75, 0.80, and 0.85, the efficiency ratio per unit length on cloudy days is 5.15%, 5.88%, and 6.62%, respectively. When the climate condition is mixed days, the efficiency ratio per unit length corresponding to the 3 m high sidewall material at the tunnel exit is the largest. When the reflectivity is 0.75, 0.80, and 0.85, the efficiency ratio per unit length in mixed days is 5.31%, 6.28%, and 6.76%, respectively.

4.1.3. Effect of Layout Method of Lamps on Actual Energy Efficiency Value. The actual energy efficiency value refers to the power consumption of lamps when the luminance value reaches 100lx per square meter on the road surface. In other

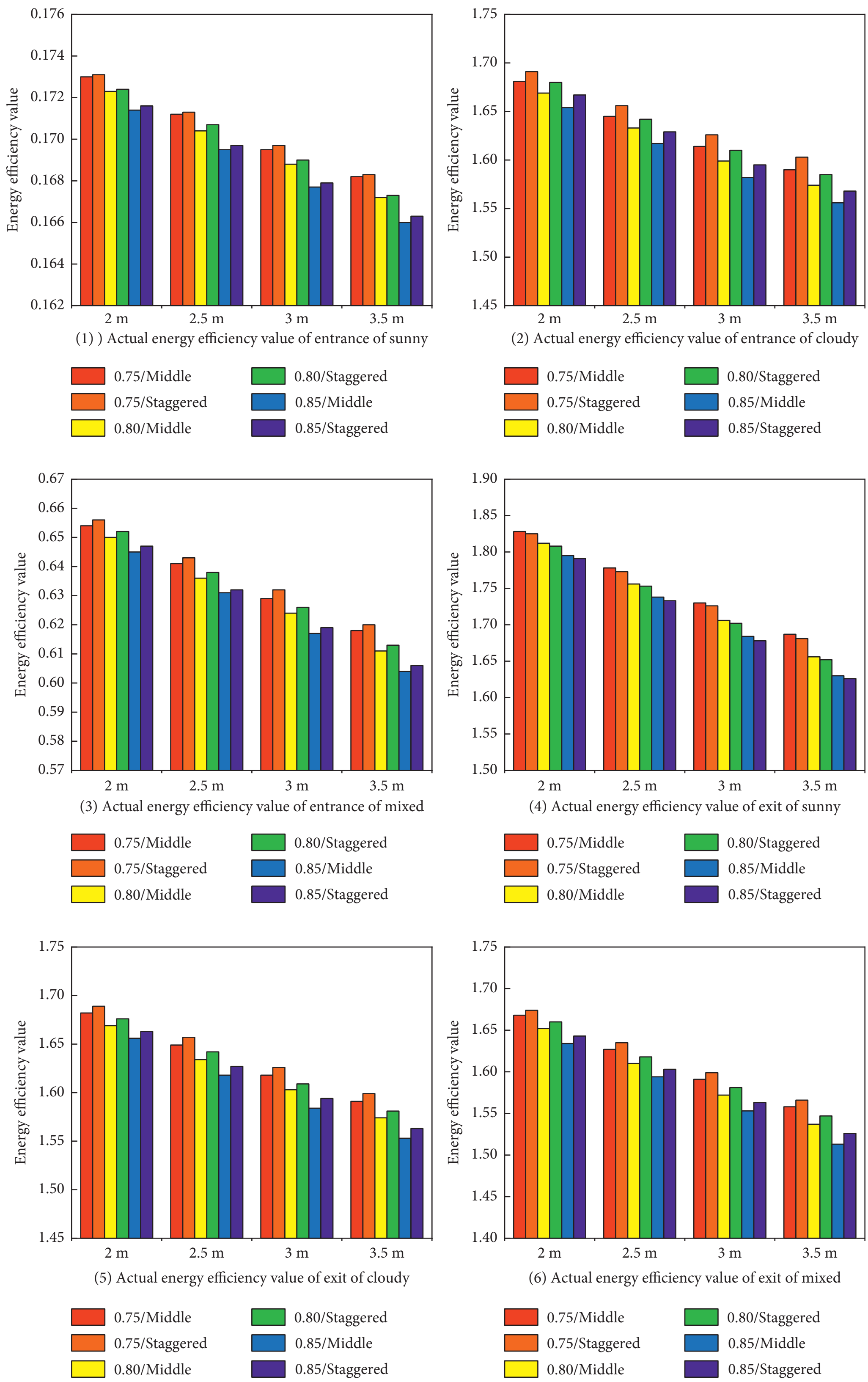


FIGURE 7: The actual energy efficiency value with different layout methods of lamps. (a) Actual energy efficiency value of entrance of sunny. (b) Actual energy efficiency value of entrance of cloudy. (c) Actual energy efficiency value of entrance of mixed. (d) Actual energy efficiency value of exit of sunny. (e) Actual energy efficiency value of exit of cloudy. (f) Actual energy efficiency value of exit of mixed.

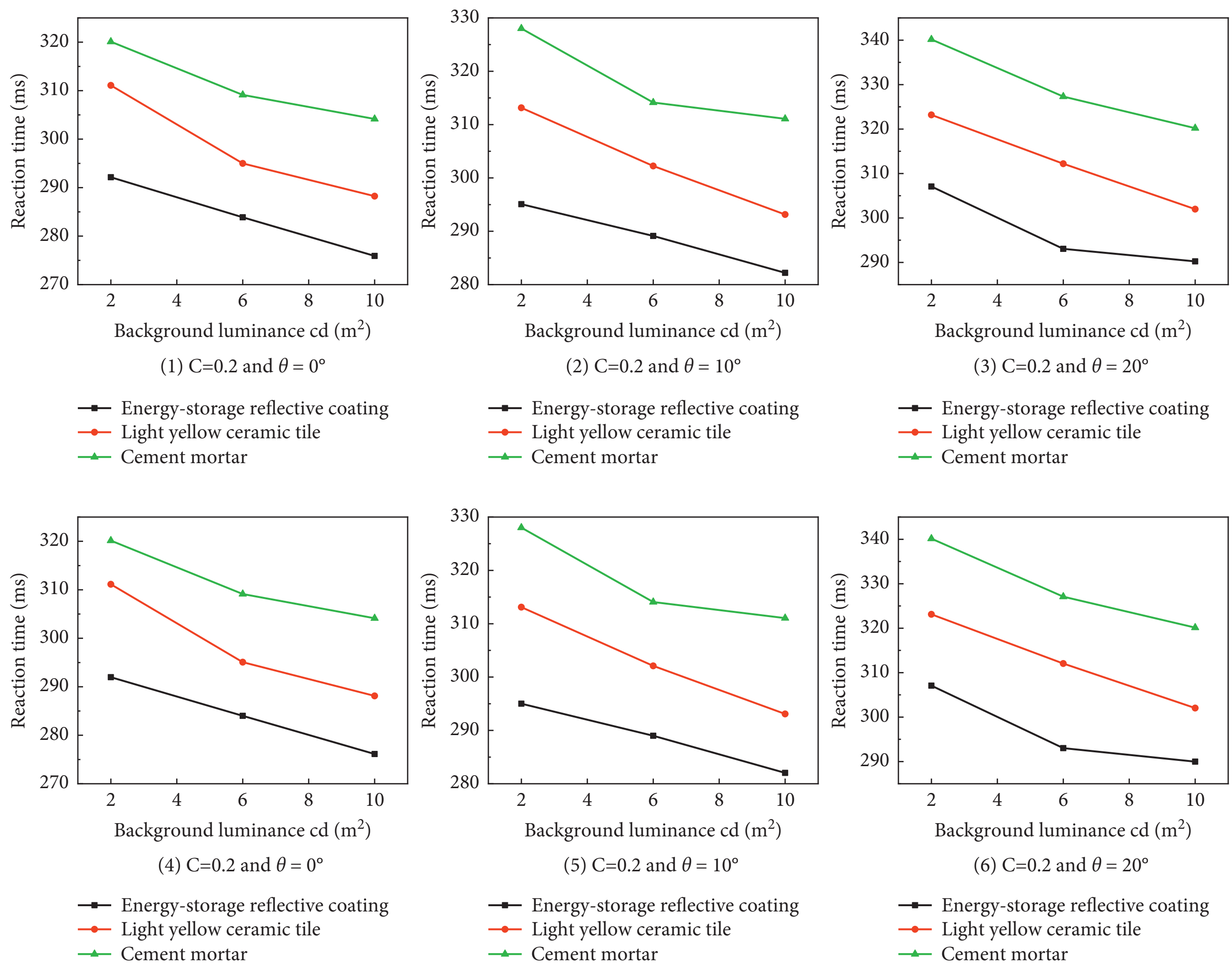


FIGURE 8: The mean value of reaction time of participants at different conditions. (a) $C = 0.2$ and $\theta = 0°$. (b) $C = 0.2$ and $\theta = 10°$. (c) $C = 0.2$ and $\theta = 20°$. (d) $C = 0.2$ and $\theta = 0°$. (e) $C = 0.2$ and $\theta = 10°$. (f) $C = 0.2$ and $\theta = 20°$.

words, the smaller the actual energy efficiency value is, the less electric energy consumed is. The actual energy efficiency value corresponding to the entrance and exit of the tunnel under the two layout forms is shown in Figure 7. When the climate condition is clear days and the reflectivity of the sidewall is constant since the entrance of the tunnel is greatly affected by the direct sunlight, the actual energy efficiency value of the lamp is small at this time, and the difference in the actual energy efficiency values corresponding to the two layout forms is only 0.06%~0.18%. When the climate condition is cloudy and mixed days, the difference in the actual energy efficiency values of the two layout forms is 1%. In other words, the staggered layout of the lamps at the entrance of the tunnel consumes less power, which is more conducive to energy saving. In addition, when the climate condition is clear days, the actual energy efficiency value with the middle layout at the exit of the tunnel is 0.16%~0.35% lower than that of the staggered layout. When the climate condition is cloudy and mixed days, the actual energy efficiency value with a staggered layout at the entrance of the tunnel is 0.42%~0.64% lower than that of staggered layout.

4.2. Experimental Results and Discussion. The relationship between the reaction time of participants and background luminance under two kinds of contrast is described in Figure 8. As shown in Figures 8(a)–8(c), it can be seen that the reaction time of the participants decreases with the increase of background luminance. When the background luminance is 2 cd/m2, the reaction time is the longest. When the background luminance reaches 10 cd/m2, the reaction time under the action of three kinds of sidewall materials all reached the minimum, and the reduction speed of the reaction time slowed down with the increase of background luminance. When the background luminance is within the range of 2 cd/m2–10 cd/m2, the response time corresponding to the energy-storage reflective coating is shorter than that of the other two materials. When the contrast is 0.2, the eccentricity is 0°, and the background luminance is 10 cd/m2, the minimum response time can be obtained as 276 ms. In addition, the response time corresponding to the energy-storage reflective coating on the sidewalls decreases slightly less than the other two materials with the increase of the background luminance.

In addition, when the contrast is 0.5, the eccentricity is 0°, and the sidewall materials of the tunnel are energy-storage reflective coating, the driver's reaction time decreased from 271 ms to 256 ms as the background luminance increased from 2 cd/m2 to 10 cd/m2. When the contrast is 0.5, the eccentricity is 10°, and the sidewall materials of the tunnel are energy-storage reflective coating, the driver's reaction time decreased from 282 ms to 263 ms as the background luminance increased from 2 cd/m2 to 10 cd/m2. When the contrast is 0.5, the eccentricity is 20°, the sidewall materials of the tunnel are energy-storage reflective coating, and the driver's reaction time decreases from 296 ms to 277 ms as the background luminance increases from 2 cd/m2 to 10 cd/m2. The change law of reaction time corresponding to the other two materials is similar. In summary, with the increase of background luminance, the reaction time of drivers decreases. Meanwhile, applying energy-storage reflective coating on the sidewalls of the tunnel has a better effect than using light yellow ceramic tiles and cement mortar on the sidewalls.

5. Conclusion

The 24-hour artificial lighting of the tunnels consumes a large amount of electricity, which means increased environmental damage and carbon footprint for China, which is dominated by thermal power. In this study, based on the Wanxichong extra-long tunnel in Yunnan Province, the simulation and experimental research were conducted at the entrance section, middle section, and exit section of the tunnel to evaluate the energy consumption of the tunnel from the perspective of environmental sustainability. The effects of different climate conditions, layout methods of lamps, and the reflectivity of sidewall materials on the tunnel lighting quality and energy-saving effect at entrance and exit are investigated by using the simulation method. At the same time, the test parameters such as type of sidewall materials, contrast, background luminance, and eccentricity are selected to investigate the reaction time of the participants by using the indoor lighting environment simulation system of a highway tunnel. The main conclusions are summarized as follows:

(1) The greater the brightness of natural light, the more obvious the improvement effect of the sidewall material on the lighting quality at the entrance and exit of the tunnel. When the reflectivity is constant, the improvement of the luminance and luminance uniformity on the road surface by the sidewall material is much greater on clear days than on cloudy days, while the mixed days are between the both. With the same climate condition and layout method of lamps, the average luminance and luminance uniformity are positively correlated with the reflectivity of the sidewall material. Therefore, the high-reflectivity sidewall material on the sidewall is beneficial to improving the lighting quality and achieving the purpose of energy-saving lighting. For the same climate condition and sidewall material reflectivity, the higher the height of the sidewall material, the greater the average luminance and luminance uniformity at the entrance and exit of the tunnel. When the reflectivity of the sidewall material is constant, the use of staggered lights in the tunnel can greatly improve the luminance uniformity on the road, which is more conducive to safe driving.

(2) Firstly, the efficiency ratio per unit length at the tunnel entrance under different climate conditions is compared. It can be seen that, on the clear days, the efficiency ratio per unit length corresponding to the 2 m high sidewall material at the tunnel entrance is the largest, but on the cloudy days and mixed days, the efficiency ratio per unit length corresponding to the 2.5 m high sidewall material at the tunnel entrance is the largest. The efficiency ratios per unit length at the tunnel exit under different climate conditions are compared. It can be observed that, on clear days, the efficiency ratio per unit length corresponding to the 2 m high sidewall material at the tunnel exit is the largest when the reflectivity of the sidewall material is 0.75. However, the efficiency ratio per unit length corresponding to the 3 m high sidewall material at the tunnel exit is the largest when the reflectivity of the sidewall material is 0.80 and 0.85. On cloudy days, the efficiency ratio per unit length corresponding to the 2 m high sidewall material at the tunnel exit is the largest. When the climate condition is mixed days, the efficiency ratio per unit length corresponding to the 3 m high sidewall material at the tunnel exit is the largest.

(3) On cloudy and mixed days, double-sides staggered lighting should be used for the entrance and exit of the tunnel, which can achieve the maximum actual energy efficiency value, and this layout method also can improve the lighting quality of the tunnel. On clear days, it is greatly affected by natural light, and the actual energy efficiency values of the two layout methods are a little different, but double-side staggered lighting can improve the luminance uniformity, so it is advisable to use double-side staggered lighting on clear days.

(4) The reaction time of the participants decreases with the increase of background luminance, and the reduction speed of the reaction time slowed down with the increase of background luminance. Applying energy-storage reflective coating on the sidewalls of the tunnel has a shorter reaction time than using light yellow ceramic tiles and cement mortar on the sidewalls.

Data Availability

All the data obtained from several experiments are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by China Railway Siyuan Survey and Design Group Co., Ltd. (2017K075-1).

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