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Study on the Glare Phenomenon and Time-Varying Characteristics of Luminance in the Access Zone of the East–West Oriented Tunnel

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Abstract: In response to the special feature of the east–west oriented road tunnel entrance being easily exposed to direct sunlight, a study was conducted on the glare phenomenon at the access zone for this type of tunnel and on the time-varying characteristics of the L_{20}(S) value outside the tunnel. First, the actual situation of luminance difference inside and outside the tunnel was considered. Field tests were carried out in a 20° field of view of the human eye within a stopping distance. Then, the environment paraments outside the tunnel were collected by combining the environment schematic method with the digital camera method. Finally, the differences and time-varying characteristics between the measured and recommended values of luminance outside the tunnel were analyzed. The *PGSV* daylight calculation model was used to analyze the glare effect in the 20° field of view of the human eye. The results indicate that the luminance L_{20}(S) outside the tunnel towards the east (west) generally shows a trend of first increasing and then decreasing, and reaches its maximum value in the morning (afternoon). The difference in the contribution ratio of luminance inside and outside the tunnel for this type shows an overall trend of first increasing and then decreasing, and the maximum difference appears in the morning (afternoon), reaching about 97% and 96% respectively. The time-varying characteristics of glare in the access zone of an east (west) oriented road tunnel are roughly consistent with the variation trend of the luminance L_{20}(S) outside the tunnel and exceed the intolerable glare limit. Due to direct sunlight, the luminance outside the tunnel is too high, resulting in an uncomfortable glare that the driver cannot tolerate, becoming more serious after rainfall, and which affects driving comfort and safety.

Keywords: tunnel engineering; glare phenomenon; time-varying characteristic of luminance; east–west oriented tunnel; L_{20}(S)

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1. Introduction

China's process of highway construction is gaining momentum, leading to an increase in the scale and number of highway tunnels [1]. Consequently, the scale and number of tunnel lighting facilities are also on the rise. This expansion, however, brings with it certain challenges, such as a noticeable increase in energy consumption due to tunnel lighting and a rise in the rate of traffic accidents. Tunnels oriented from east to west are relatively common in current construction projects, yet they also present their own set of problems. Due to the particularity of the direction of the east–west highway tunnel and the trend of the sun rising in the east and setting in the west, the brightness outside the tunnel near the tunnel is larger in the morning (afternoon). Therefore, the luminance difference between inside and outside the tunnel is large and the resulting glare phenomenon is caused. The phenomenon of glare in the access zone will increase the driver's visual burden and prolong the driver's identification and judgment time of tunnel road conditions, which will readily cause the driver to be unable to accurately judge the road conditions ahead and thus generate safety risks [2]. Disability glare is a physiological term that is caused by distracting light from a glare source scattering onto the surface of the retina, like a large screen on the retina, reducing the contrast of images on the retina, resulting in reduced visibility [3]. During the driving process, poor luminance distribution in the driver's field of vision causes glare problems, thus negatively affecting visual perception [4]. The access zone of a road tunnel refers to the length of the stopping sight distance for one time outside the tunnel entrance. As the transitional adaptation section is before the driver enters the tunnel, the safety of the access zone is particularly important.

$L_{20}(S)$ is a key index for studying the external luminance of the tunnel in the access zone. $L_{20}(S)$ represents the average luminance of a 20° conical field of view when an observer at the start of the access zone looks towards a central point located at one quarter of the tunnel portal height. Scholars have carried out a series of studies on the $L_{20}(S)$ outside the tunnel and the glare phenomenon in the access zone of the east–west oriented road tunnel, and have obtained certain results. Reference [5] measured 12 real tunnels, and it was concluded that the $L_{20}(S)$ of the east–west oriented tunnel is smaller than the north–south oriented tunnel. Zhao Weibin [6] in combination with different tunnel orientations, concluded that the sunlight of the tunnel facing east in the morning and that of the tunnel facing west in the afternoon is stronger and the luminance outside the tunnel is larger, which is extremely unfavorable to traffic safety near the tunnel. Huang Mingfa [7] believed that the main reason for the safety problems in the access zone of the tunnel was the "black-hole effect" in the threshold zone, that is, the visual blindness period in the threshold zone. In the field of tunnel lighting, the research on glare in road tunnels has mainly focused on the road lighting and automobile lighting, and the glare threshold increment TI and glare control level G are mainly used as the guiding standards for highway lighting design [8]. Pan Beibei et al. [9] believe that asphalt pavement with a low reflection coefficient should be used in the tunnel approach section to reduce the external luminance of the tunnel, to improve the "black-hole effect" in the tunnel approach section. Yuan Li et al. [10] analyzed the influence of central divider greening on the anti-glare effect. By comparing the anti-glare structures of different tunnel doors, Ai Jie et al. [11] concluded that the shading shed at the tunnel entrance can not only solve the transition problem of road dimming, but also achieve the effect of anti-glare. Yu Xu [12] et al. established a quantitative evaluation method for discomfort glare caused by the dark area illuminated by sunlight in the sunshade canopy, and the results showed that the glare value UGR of the equal-distance sunshade canopy was smaller than that of the unequal-distance sunshade canopy. Yang Shaowei [13] studied the anti-glare plant height calculation method in the central partition of the access zone, to replace engineering anti-glare facilities and achieve better ecological and landscape benefits. Xiao Yao et al. [14] analyzed the glare effect caused by the unreasonable luminance transition at the exit zone, and proposed a gradient layer design method based on the anti-glare principle. It can be seen from the above that the current research on the external luminance $L_{20}(S)$ of the east–west highway tunnel has been limited to expounding the variation of the external luminance value of the east–west road tunnel. Due to the particularity of tunnel orientation, it has a certain impact on traffic safety, but the relationship between east–west orientation factors and the variation rule of $L_{20}(S)$ outside the tunnel has not been studied in depth. At the same time, the studies on the glare phenomenon of the highway tunnel have been basically limited to the "black-hole effect" in the tunnel entrance section, the glare of lamps inside the tunnel, the "white-hole effect" in the tunnel exit section, and the anti-glare measures of the engineering outside the tunnel. At present, there are few corresponding studies available on the relationship between the glare of different orientations and the time-varying characteristics of the luminance $L_{20}(S)$ outside the tunnel. Therefore, the influence of indirect glare caused by luminance difference inside and outside the tunnel and the surroundings outside the tunnel on the visual environment quality of the access zone has been ignored.

Currently, a lot of the research on tunnel glare is based on the analysis of a 20° line of sight angle. That is, when the angle between the glare source light and the driver's line of sight is 20°, theoretically, it is easy to produce glare phenomenon. But this theory only applies to fixed direct glare light sources, such as lighting fixtures and other devices. However, the glare produced by the landscape and road surface outside the tunnel is irregular, and it is difficult to determine the angle of glare by the above theory. Combined with the east–west orientation factor, sunlight will be directly on the tunnel portal in the morning and afternoon, making the 20° field of view brighter outside the tunnel surroundings and road surface forming an indirect glare. Combined with the large luminance difference between inside and outside the tunnel, the driver's visual load will be increased in this case, and it will directly affect the driving safety and comfort of the access zone. In terms of luminance outside the tunnel, CIE 88-2004 [15] proposed a field of view range of 20° of human vision based on the stopping sight distance from the tunnel entrance, in which the 20° field of view covers the 20° angle between the glare light source and the driver's line of sight that is prone to glare. That is, the glare phenomenon readily occurs in the 20° field of view of the external brightness proposed by CIE. The 20° field of view of the external luminance $L_{20}(S)$ can solve the problem where it is difficult to determine the angle of glare. At the same time, the division principle of the landscape inside and outside the tunnel in the 20° field of view just divides the indirect glare light source and the glare background outside the cave. Therefore, the 20° field of view proposed by CIE is used in this study to analyze the time-varying characteristics (trend and rule) of the external luminance $L_{20}(S)$ and uncomfortable glare in the access zone of the east–west road tunnel. Combined with theoretical and field test data, this study aims to study the relationship between the external luminance and uncomfortable glare at the approaching section. The research results can provide a reference for improving the visual environment quality of driving in the tunnel approach section and the design of $L_{20}(S)$ and the surroundings outside the tunnel, as well as to enrich the research content of the glare outside the tunnel in the access zone. At the same time, the research methods of 20° field of view and quantification of indirect glare source can provide a new research direction for non-luminaire external glare and other structures with outdoor glare.

In this study, a field test was conducted using a combination of the environmental schematic method and the digital camera method. The difference between the measured $L_{20}(S)$ value outside the tunnel and the recommended value, along with its time-varying characteristics, were analyzed. This also included the predicted glare sensation vote (*PGSV*) within the 20° field of view.

The structure of this paper is as follows: In Section 2, field tests are conducted and the luminance value $L_{20}(S)$ outside the tunnel is collected. In Section 3, we analyze the time-varying characteristics of the $L_{20}(S)$ value in the east–west tunnel and the difference in luminance contribution ratio inside and outside the tunnel. In Section 4, the predicted glare sensation vote (*PGSV*) daylight calculation model is used to analyze the glare value in the access zone of the east–west oriented road tunnel.

2. Materials and Methods of Field Test

2.1. Index of Field Test

2.1.1. Luminance Outside the Tunnel $L_{20}(S)$

The luminance outside the tunnel $L_{20}(S)$ refers to the average luminance measured in the field of view of 20° in the direction of the tunnel entrance, 1.5 m above the ground, at the distance of a stopping sight distance from the tunnel entrance. The luminance outside the tunnel is one of the important reference parameters of tunnel lighting design, and the rationality of this parameter has a great influence on the setting of the light distribution curve of road tunnel lighting and the energy consumption of road tunnel lighting [16]. The schematic diagram is shown in Figure 1.

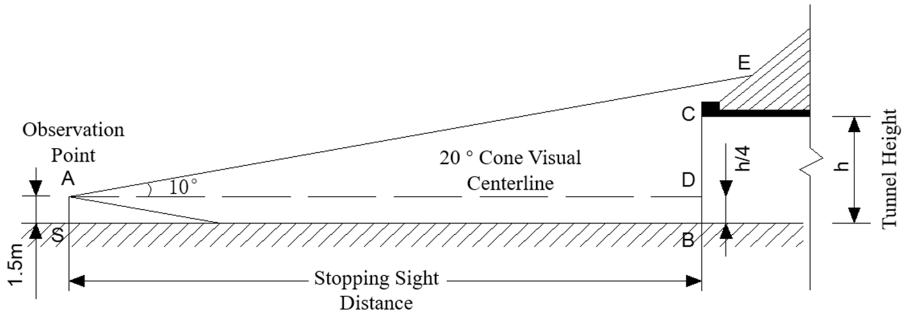

Figure 1. Schematic of L_{20}(S) test.

2.1.2. Glare

In the International Commission on Illumination (CIE), glare is defined as a visual condition that is formed due to an inappropriate luminance distribution, a significant change in luminance, or extreme spatial and temporal contrasts that cause discomfort to the observer or reduce their ability to observe important objects, or both phenomena [17–19], namely, disabling glare and discomfort glare. Disability glare can cause a decrease in the visibility of the driving environment and the driver's vision, which can easily lead to driving accidents; however, discomfort glare is often caused by strong brightness environments and uneven distribution of luminance [17]. It only brings discomfort and does not lead to a decrease in the driver's vision [20].

2.2. Method and Scheme of Field Test

2.2.1. Test Method of Field Test

This test is based on the "Guidelines for Design of Lighting of Highway Tunnels" issued by the Ministry of Transport of the People's Republic of China [21], which considers three factors: sky rate, tunnel door orientation, and design speed to calculate the L_{20}(S) value of the luminance outside the tunnel. Under the same sky rate and the same design speed of the highway tunnel, analysis is of the time-varying characteristics of glare phenomenon and external luminance in the access zone of the east–west oriented tunnel.

Based on the method of combining the environmental schematic method and the digital camera method [22], a digital camera Canon PowerShot SX720 HS was set up at a stopping sight distance from the tunnel access zone and at a height of 1.5 m from the ground to record the situation of the tunnel approach section at this time. The direction of the digital camera was along the axis of the tunnel. Then the PR-655 spectral radiation luminance meter was installed in the same position to record the luminance of the sky, the luminance of the tunnel entrance, the luminance of the tunnel, and the luminance of the scenery around the tunnel entrance. During this process, the luminance meter was also aimed towards the direction of the tunnel entrance to obtain the corresponding luminance value at that position. Finally, the scenery within 20° of the visual field of the human eye was divided into blocks using Autodesk AutoCAD 2014, which can generally be divided into sky, entrance, surroundings, and road surface. The tunnel segmentation diagram is shown in Figure 2.

The procedure is carried out as follows. View the area of each block in Autodesk AutoCAD 2014., then calculate the sum of the product of each block luminance value and the corresponding area percentage, and finally obtain the L_{20}(S) value of the road tunnel external luminance [23]. The calculation formula is shown in Equation (1).

$$L_{20} = \gamma \cdot L_c + \rho \cdot L_r + \varepsilon \cdot L_e + \tau \cdot L_{th} \quad (1)$$

where, L_c = luminance of the sky, γ = % of sky in the 20° field; L_r = luminance of the road, ρ = % of road; L_e = luminance of the surroundings, ε = % of surroundings; L_{th} = luminance of the threshold zone, τ = % of tunnel entrance.

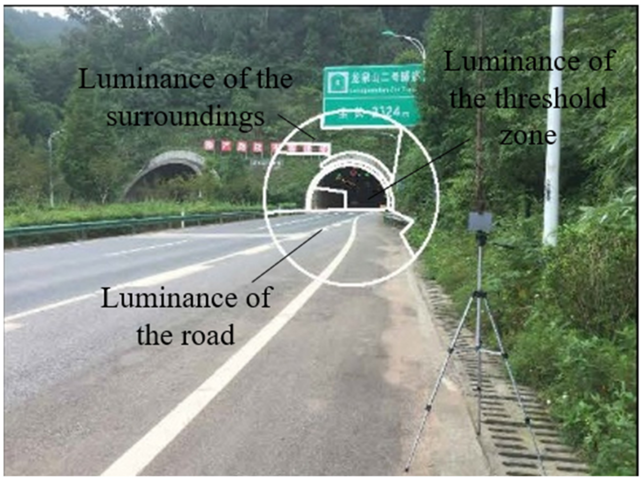

Figure 2. Test block diagram of Longquanshan No. 2 Tunnel.

2.2.2. Test Scheme

According to the definition of glare value, glare phenomenon is caused by improper luminance distribution or extreme contrast in space and time, and the luminance outside the tunnel is determined by dividing the 20° field of view of the human eye according to the surroundings inside and outside the tunnel entrance. Therefore, in the 20° field of view, there will also be inappropriate luminance distribution inside and outside the entrance of the tunnel and huge brightness difference. Based on this, this study focused on analyzing the time-varying characteristics of glare caused by improper luminance distribution in the 20° field of view of the human eye divided by the luminance $L_{20}(S)$ outside the tunnel.

A total of eight tunnel entrances were selected for the testing plan, and the tests were conducted in summer and winter, respectively. The daily testing time was from 9:00 a.m. to 17:00 p.m., and the testing was conducted on the hour. Depending on the specific situation, the number of tests per day was 8 to 9. During the testing process, severe lighting at the entrance of the tunnel during the morning and afternoon periods, as well as post rain conditions, were marked to analyze the glare phenomenon in the east–west direction of the highway tunnel. Based on the environmental diagram method recommended by CIE, this article first analyzed the time-varying characteristics of the $L_{20}(S)$ value of the luminance outside the east–west direction road tunnel. Further testing and calculation of the difference in luminance between the inside and outside of the entrance within a 20° field of view, as well as the contribution ratio to the luminance outside the entrance (the product of brightness value and corresponding area percentage to the percentage of luminance outside the entrance), were conducted. At the same time, the daylight calculation model *PGSV* value was introduced to analyze each working condition, and obtain the time-varying characteristics of glare phenomenon in the access zone of the east–west oriented tunnel based on the $L_{20}(S)$ outside the entrance. From this, we delve into the fundamental reasons that endanger the safety of driving in the access zone of the tunnel.

2.3. Test Subject of Field Test

We selected tunnels with the same sky rate, design speed, and east–west orientation as test subjects. After the investigation of highway tunnels in Chongqing and Sichuan Province, except for highways or expressways, which are inconvenient for field testing, six tunnels were selected as the research object: Youyi Tunnel, Tiangangtang Tunnel, Longquanshan No. 1 Tunnel, Longquanshan No. 2 Tunnel, Tongmao Tunnel (Northwest and due East). Detailed parameters of the tunnels are shown in Table 1.

Table 1. Related parameters of tunnels.

Tunnel	Orientation	% of Sky	Design Speed	Stopping Sight Distance	Portal Form	Weather	Season
Youyi Tunnel	North by West 82°	0%	40 km/h	26 m	End Wall	Sunny	Summer
Tiangongtang Tunnel	Due East	0%	40 km/h	26 m	Slanting Cut	Cloudy	Summer
Longquanshan No. 1 Tunnel	Due West	0%	60 km/h	56 m	Slanting Cut	Cloudy	Summer
Longquanshan No. 2 Tunnel	North by West 70°	0%	60 km/h	56 m	Slanting Cut	Cloudy	Summer
Tongmao Tunnel (Northwest)	North by West 70°	0%	80 km/h	100 m	Slanting Cut	Cloudy	Winter
Tongmao Tunnel (Due East)	Due East	0%	80 km/h	100 m	End Wall	Sunny	Winter
Tiangongtang Tunnel	North by West 82°	0%	40 km/h	26 m	End Wall	Sunny	Summer

3. Results

3.1. Time-Varying Characteristics of $L_{20}(S)$ in Due East Oriented Road Tunnel

Field tests were carried out on the two east oriented tunnels in Table 1, respectively. The test data were processed, and the results are shown in Figures 3 and 4. The measured luminance $L_{20}(S)$ outside the portal of the east oriented tunnel has the maximum value in the morning. In summer and winter, the overall trend of the luminance value outside the east oriented tunnel is first increased and then decreased, and the maximum value appears at about 11:00 p.m. In the morning, the access zone of the east oriented tunnel is directly exposed to sunlight, resulting in greater luminance outside the tunnel, which also exacerbates the difference in luminance inside and outside the tunnel. Previous studies also believed that excessive luminance difference readily affects the driver's visual judgment, thus affecting driving safety.

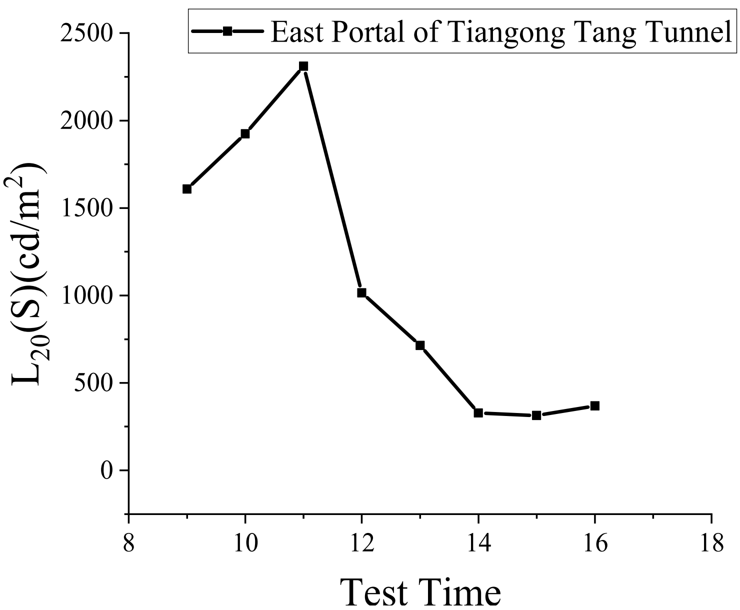

Figure 3. Measured $L_{20}(S)$ value at the east portal of Tiangongtang Tunnel (Summer).

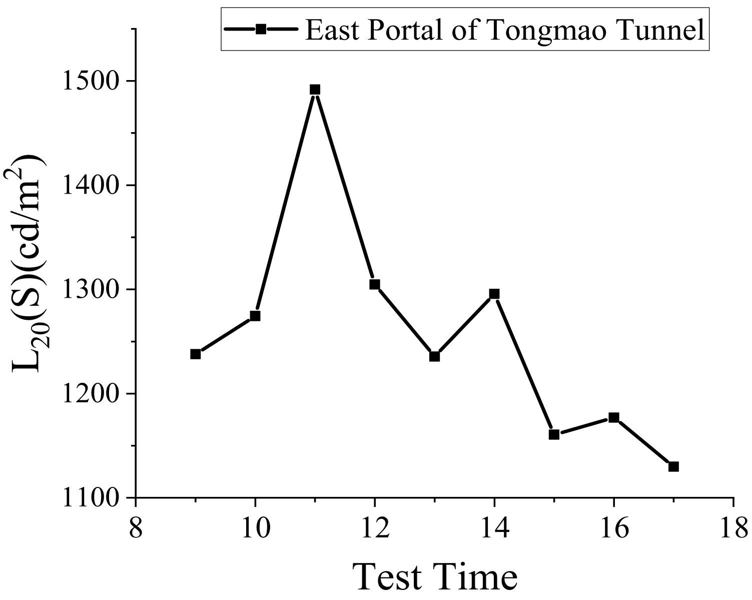

Figure 4. Measured $L_{20}(S)$ value at the east portal of Tongmao Tunnel (Summer).

3.2. Time-Varying Characteristics of $L_{20}(S)$ in Due West Oriented Road Tunnel

Field tests were carried out on the remaining four tunnels. The test data were processed, and the results can be seen in Figures 5–8. The measured luminance $L_{20}(S)$ outside the portal of the west oriented tunnel has the maximum value in the afternoon. In summer and winter, the brightness value outside the west portal of the tunnel increases first and then decreases and reaches its maximum value from 14:00 p.m. to 16:00 p.m. in the afternoon. Due to the direct sunlight, the luminance outside the tunnel is large and the difference between the luminance inside and outside the tunnel is intensified. Correspondingly, it will also affect safe driving in the access zone.

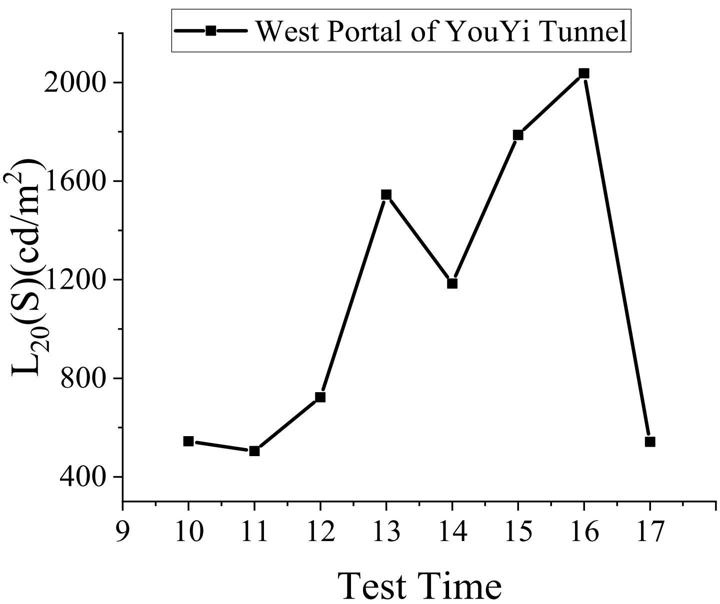

Figure 5. Measured $L_{20}(S)$ value at the west portal of Youyi Tunnel.

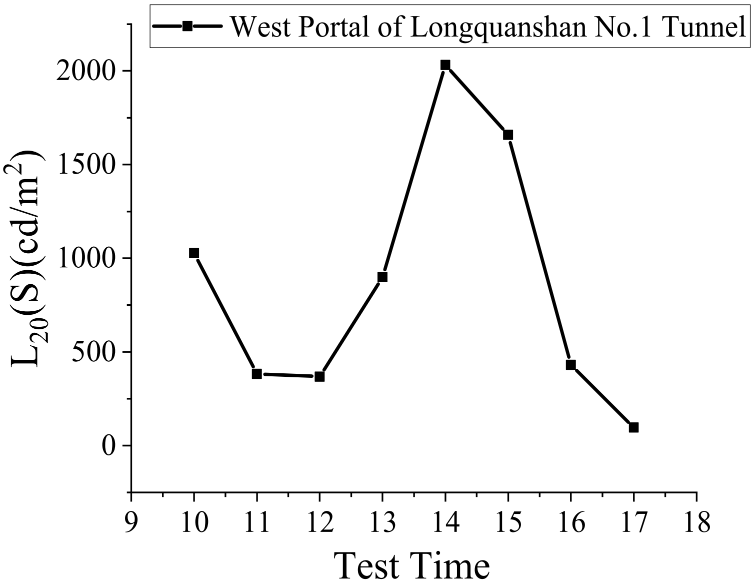

Figure 6. Measured L_{20}(S) value at the west portal of Longquanshan No. 1 Tunnel.

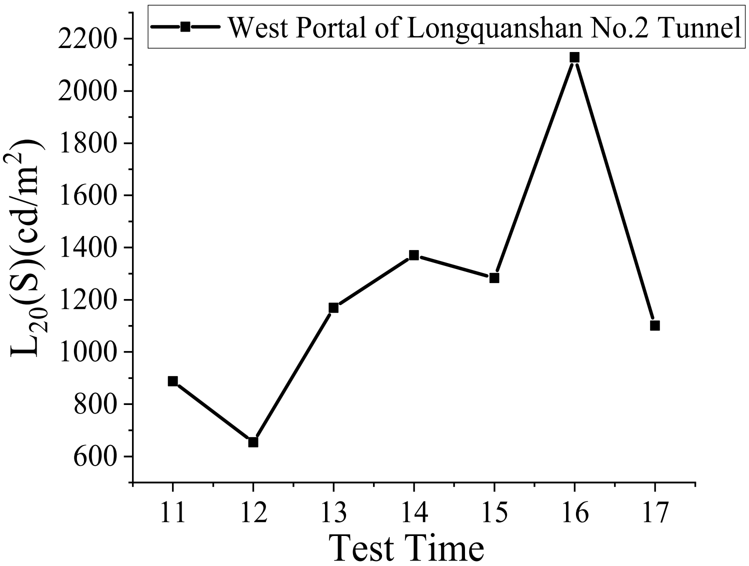

Figure 7. Measured L_{20}(S) value at the west portal of Longquanshan No. 2 Tunnel.

Due to the limitations of the test conditions, although Youyi Tunnel, Longquanshan No. 2 Tunnel and Tongmao Tunnel (Northwest) are not in absolute due west orientation, they are very close to the due west orientation (deviations of 8°, 20°, and 20°, respectively), so they have little impact on the analysis results. In addition, the glare phenomenon and time-varying characteristics are discussed in this paper to explore the law of change, so the absolute value does not have much influence on the study.

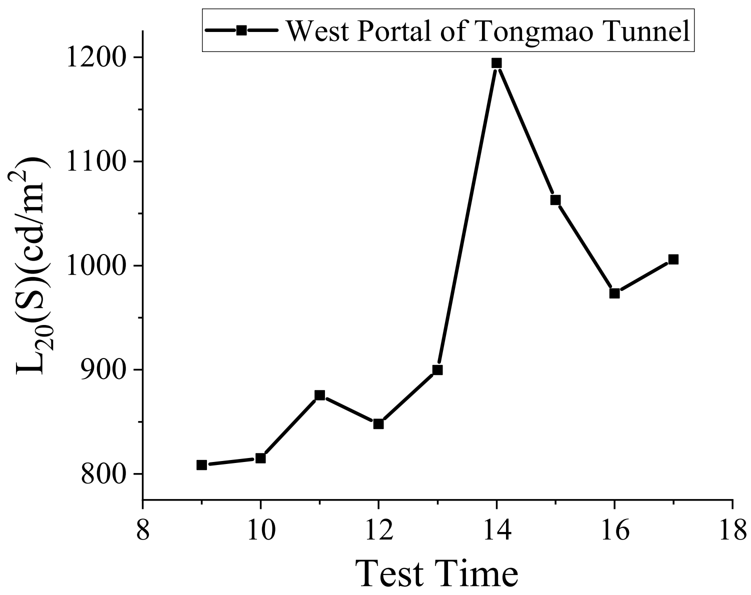

Figure 8. Measured $L_{20}(S)$ value at the west portal of Tongmao Tunnel.

3.3. Contribution Ratio of the Luminance of the East–West Oriented Tunnel

From the above two sections, the access zone of the east oriented tunnel and the west has more sunlight and luminance outside the tunnel during the morning and afternoon periods, respectively. According to the definition of glare, when the difference of luminance distribution outside the tunnel is too large, uncomfortable glare readily appears in the tunnel access zone. The luminance contribution ratio of landscape environment factors outside the tunnel within the 20° field of view is introduced to quantify the difference of luminance inside and outside the tunnel near the section. That is, the relationship between the external luminance value and the area percentage product value in the 20° field of view and the total luminance $L_{20}(S)$ value in the 20° field of view makes the difference comparison of external luminance more intuitive. Among them, the environmental elements in the 20° field of view are mainly composed of three aspects: tunnel entrance, surroundings outside the tunnel, and road surface outside the tunnel. It is considered that the surroundings outside the east–west oriented tunnel are irradiated by sunlight to form an indirect glare light source, which causes an uncomfortable glare phenomenon. Therefore, the luminance of the surroundings outside the tunnel and the road surface is quantified as the indirect glare light-source luminance, and the luminance of the surroundings inside the tunnel is quantified as the glare background luminance. Then, the variation law of luminance difference outside the tunnel is analyzed to provide reference for the glare caused by indirect glare sources outside the tunnel. Figures 9 and 10 are the trend graphs of luminance values changing with time in the road tunnel facing due east and due west, respectively. Figures 11–13 show the difference of the environmental contribution ratio between the inside and outside of the tunnel in the access zone of the east–west oriented road tunnel.

As can be seen from Figure 9, the luminance in the access zone of the due east-oriented tunnel varies from 13 to 50 cd/m^2, and the luminance remains low compared with the luminance outside the tunnel. As can be seen from Figure 10, the luminance inside the access zone of the due west-oriented tunnel varies from 1.4 to 160 cd/m^2, and its value is still low compared with the luminance outside the tunnel.

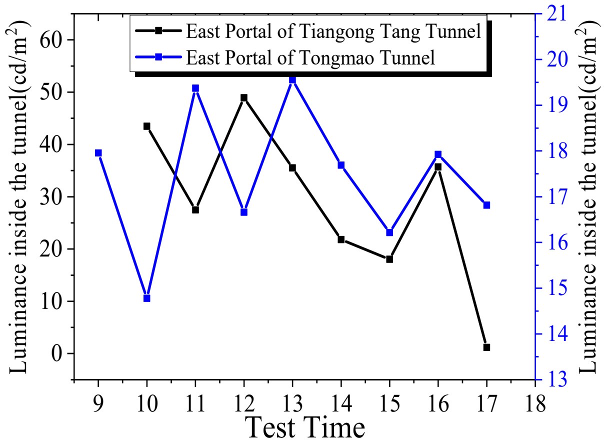

Figure 9. Luminance inside the due east oriented tunnel.

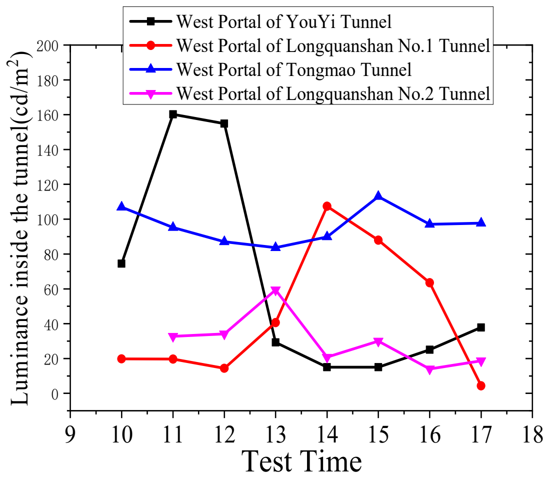

Figure 10. Luminance inside the due west oriented tunnel.

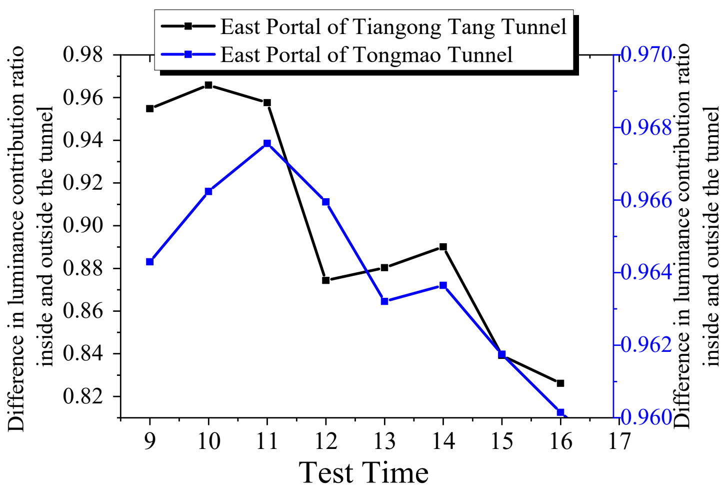

Figure 11. Difference in luminance contribution ratio of the east oriented tunnel.

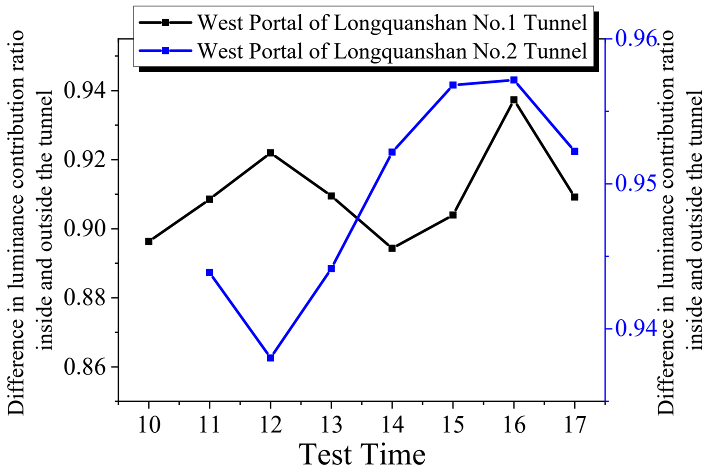

Figure 12. Difference in luminance contribution ratio of the west oriented tunnel. (Longquanshan No. 1 Tunnel, Longquanshan No. 2 Tunnel).

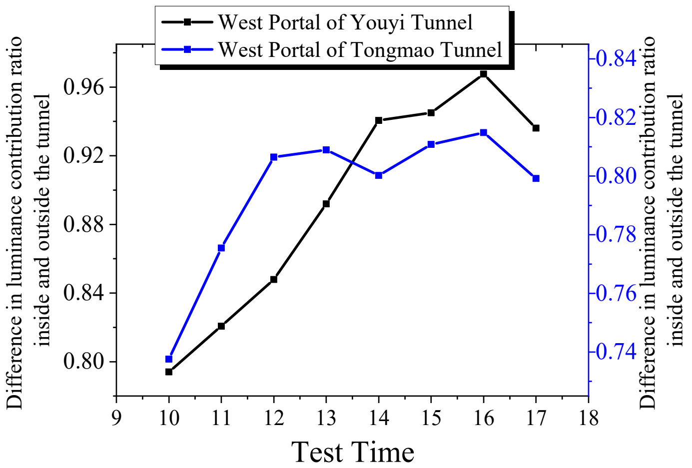

Figure 13. Difference in luminance contribution ratio of the west oriented tunnel. (Youyi Tunnel, Tongmao Tunnel).

As can be seen from Figure 11, the difference of the luminance contribution ratio outside the tunnel facing due east is generally more than 95.7% in the morning, and the maximum is nearly 97%. The difference in luminance contribution ratio in the afternoon is smaller than in the morning. As can be seen from Figures 12 and 13, the luminance contribution ratio of the due west oriented tunnel (except Longquanshan No. 1 Tunnel) is generally greater in the afternoon than in the morning, and the maximum difference of luminance in the afternoon is 96.8%. The luminance outside the access zone of the tunnel changes with the trend of sunlight irradiation, and generally increases first and then decreases. The luminance inside the tunnel varies from 1.4 to 160 cd/m^2, and it remains low compared to the luminance outside the tunnel. As a result, the luminance difference outside the tunnel will leads to a continuous increase with the increase of the luminance outside the tunnel. From Figures 11–13, the difference of luminance contribution outside the east and west oriented tunnels increases first and then decreases compared with the overall change trend, and the maximum difference is reached in the morning and afternoon, respectively.

From this, there is a significant difference in luminance values between the inside and outside of the tunnel within a 20° field of view. Correspondingly, the difference in luminance contribution ratio between inside and outside the tunnel is also too large. The results of the significant luminance difference obtained above are used to verify the phenomenon of glare generation in the following.

4. Discussion

4.1. Glare Value PGSV

According to the data analysis results of the field test, the difference of the brightness contribution ratio provided outside the tunnel is too large, the brightness distribution is not uniform, and the luminance is not suitable within the field of view of 20°. From the definition of glare, glare is easy to occur in the visual environment of the access zone with uneven luminance distribution.

Most of the studies on glare adopt the unified glare value URG in the standard for lighting design of buildings [24] for glare analysis. Because the URG value is limited to indoor light-source lighting, large light sources like indirect lighting and luminous ceiling lighting, it is not suitable for the glare calculation in the access zone of a road tunnel. After comparing the daylight index (DGI) proposed by Hopkinson [25] with the predicted glare sensation vote (*PGSV*) mentioned by Iwata and Tokura [26], the *PGSV* daylight calculation model was selected to analyze the glare effect in a 20° field of view of a road tunnel. A tunnel entrance with low luminance in the 20° field of view is regarded as the dark background, and the indirect glare formed by the surroundings and road surface outside the east–west oriented tunnel is regarded as the bright background in order to analyze the glare phenomenon. Part of the measured tunnel light and dark block diagram is shown in Figure 14. The *PGSV* formula of glare value is shown in Equation (2):

$$PGSV = 3.2 logL_s - 0.64 log\omega + (0.79 log\omega - 0.61) logL_b - 8.2 \quad (2)$$

where, L_s is the luminance of light source (cd/m^2), L_b is the luminance of background (cd/m^2), and w is the solid angle (sr) formed by the light source to the human eye.

Figure 14. Road tunnel light and dark background block diagram.

PGSV is mainly determined by three factors: light source, background, and solid angle of sight. As calculated by the formula *PGSV*, *PGSV* = 0 is perceived glare, *PGSV* = 1 is acceptable glare, *PGSV* = 2 is uncomfortable glare, and *PGSV* $\geq$ 3 is intolerable glare [27]. When *PGSV* is negative, it indicates acceptable glare to the human eye [28].

4.2. Analysis of Time-Varying Characteristics of Glare in the Access Zone of East Oriented Tunnel

An analysis was conducted on the time-varying characteristics of glare in the access zone of an east oriented tunnel, as shown in Figure 15. From Figure 15, it can be observed that the overall glare value of an east oriented tunnel shows a trend of first increasing and then decreasing. In the morning, the glare value is higher than in other time periods. The uncomfortable and even intolerable glare phenomenon caused by the luminance difference between inside and outside the tunnel occurs from 9:00 a.m. to 11:00 a.m. The luminance outside the tunnel at 10:00 a.m. and 11:00 a.m. is too large, and the corresponding *PGSV* glare value is 8.41 and 7.6, respectively, which is far beyond the intolerable glare value limit.

Currently, the luminance difference between inside and outside the tunnel is 97% and 96%, which occurs at the moment when the luminance difference between inside and outside the tunnel is the largest in a day. As mentioned above, the overall trend of $L_{20}(S)$ brightness outside the hole is to increase first and then decrease, and the maximum value appears at 10:00 a.m. The overall variation trend of the luminance difference degree inside and outside an east oriented tunnel also increases first and then decreases. The time-varying characteristics of glare are roughly consistent with the $L_{20}(S)$ value of the luminance outside the tunnel and the overall variation trend of the luminance difference degree. When the east–west oriented tunnel entrance and the surroundings are directly exposed to sunlight, the luminance outside the tunnel increases accordingly. Because the luminance of the tunnel entrance remains extremely low, the degree of luminance difference between the inside and outside of the tunnel increases on approach. This leads to the phenomenon of inappropriate luminance in the visual environment at the access zone of an east–west oriented road tunnel, resulting in uncomfortable glare at the access zone. Therefore, when the access zone is exposed to direct sunlight, the increase in luminance outside the tunnel will not only affect the design of the tunnel lighting distribution curve and increase the lighting energy consumption, but also increase the difference in luminance inside and outside the tunnel, leading to uncomfortable glare. In severe cases, it will affect the driver's driving comfort and safety.

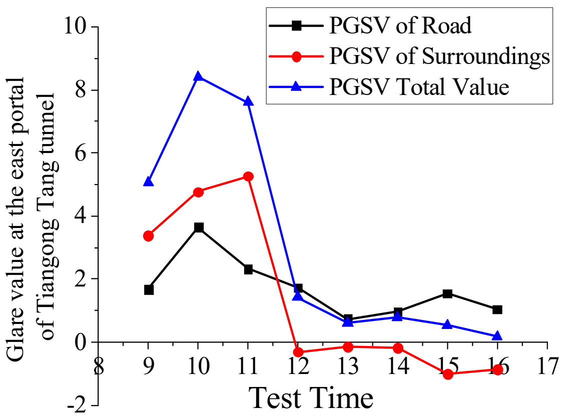

Figure 15. *PGSV* for the east gate of the Tiangongtang Tunnel.

4.3. Analysis of Time-Varying Characteristics of Glare in the Access Zone of West Oriented Tunnel

An analysis was conducted on the time-varying characteristics of glare in the access zone of a west oriented tunnel, as shown in Figures 16 and 17. From Figures 16 and 17, the glare value of the tunnel facing west generally shows an increasing trend followed by a decreasing trend, with a higher glare value in the afternoon compared to other time periods. Uncomfortable and intolerable glare appeared from 15:00 p.m. to 16:00 p.m., which was caused by the difference in luminance inside and outside the tunnel. The luminance of the Youyi Tunnel from 15:00 p.m. to 16:00 p.m. is too large, reaching 1.03 and 1.79 times of the recommended value of the "Guidelines for Design of Lighting of Highway Tunnels", respectively, which is unreasonable. At this time, the *PGSV* values were 2.91 and 3.22, respectively, reaching the intolerable glare value limit. Currently, the corresponding luminance difference outside the tunnel is about 95% and 97%, which occurs at the moment when the luminance difference inside and outside the tunnel is the largest in a day. The overall trend of the $L_{20}(S)$ is to increase first and then decrease, and the maximum value appears from 14:00 p.m. to 16:00 p.m. At the same time, the overall change trend of the luminance difference degree inside and outside the tunnel due west is also to increase first and then decrease. Therefore, the time-varying characteristics of glare are roughly the same as the $L_{20}(S)$ value and the difference degree of luminance inside and outside the tunnel. So, when the tunnel entrance and the surroundings are directly exposed to sunlight, the luminance outside the tunnel increases. Since the luminance inside the tunnel is always maintained in a very low state, and the luminance difference between inside and outside the tunnel is large, this leads to the phenomenon of improper luminance in the visual environment at the access zone of an east–west oriented road tunnel, resulting in uncomfortable glare and disabling glare at the access zone, which will seriously affect driving safety and comfort. As can be seen from Figures 13–17, the luminance difference between the inside and outside of the Tongmao tunnel is less than 82%, and the luminance inside the tunnel is higher than that of other tunnels. Therefore, there was almost no uncomfortable or even intolerable glare phenomenon in the Tongmao tunnel during the test. There is an indirect uncomfortable glare phenomenon caused by the difference of luminance inside and outside the tunnel due to the excessive luminance outside the tunnel. Therefore, the influence of the uncomfortable glare on the visual environment of the tunnel should be considered in the lighting design of the road tunnel with the direction of east to west. At the same time, the adverse effects of glare in the access zone should be considered in the design of luminance and surroundings outside the tunnel to improve the driver's driving safety and comfort.

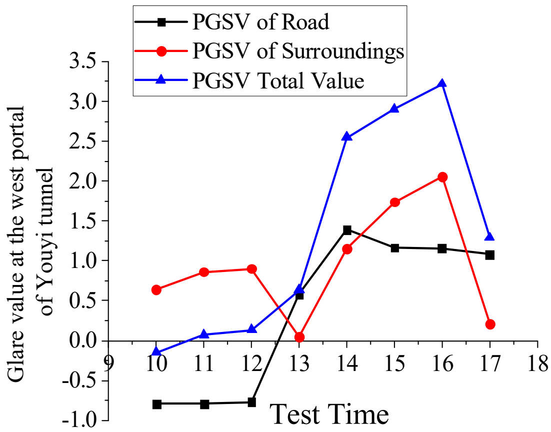

Figure 16. PGSV for the west portal of the Youyi Tunnel.

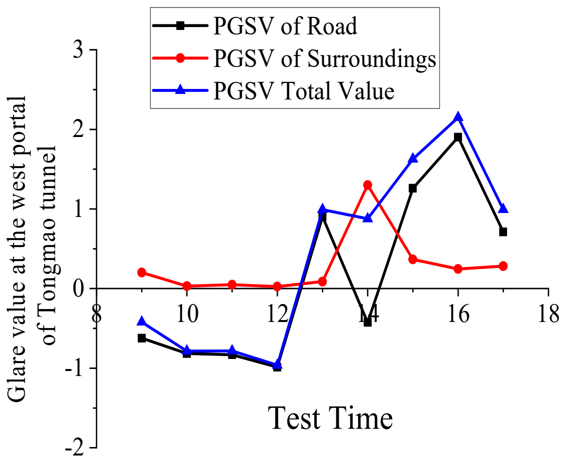

Figure 17. *PGSV* for the west portal of the Tongmao Tunnel.

4.4. Analysis of Time-Varying Characteristics of Glare after Rainfall in the Access Zone of West Oriented Tunnel

Generally, during or after rainfall, the luminance outside the tunnel will decrease due to weather conditions. However, after rainfall, the scenery outside the tunnel and the surface of the road surface can readily form indirect glare sources when combined with water, thus directly affecting the driver's glare. Therefore, considering the actual situation of driving after rainfall, the glare problem in the tunnel conditions after rain was analyzed, and the results are shown in Figure 18.

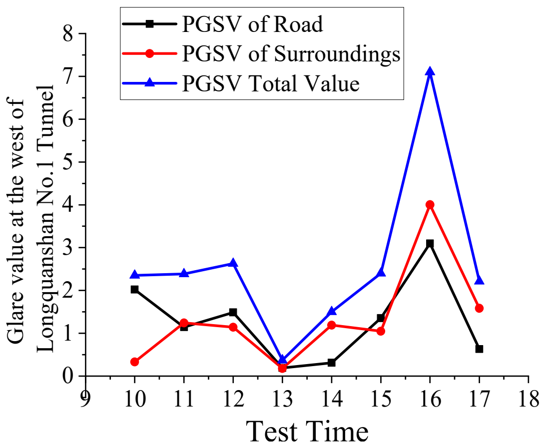

Figure 18. *PGSV* for the west portal of the Longquanshan No. 1 Tunnel.

During the test of Longquanshan No. 1 Tunnel, rain occurred during 10:00–12:00 a.m. and 16:00 p.m., respectively. The surroundings in the access zone and the road surface were wet and there was a reflective phenomenon. As can be seen from Figure 18, from 10:00 a.m. to 12:00 a.m., *PGSV* glare values of Longquanshan No. 1 Tunnel were 2.3515, 2.3831, and 2.6262, respectively, which exceeded the uncomfortable glare limits. The corresponding luminance difference between inside and outside the tunnel is 90%, 91%, and 92.2%, respectively. According to the *PGSV* glare value of the daylight model, the *PGSV* glare value after rain is greater than the *PGSV* glare value at the maximum luminance outside the tunnel (14:00 p.m.). It is not difficult to find that the glare effect after rainfall is very serious in the field of view of 20° luminance outside the tunnel. At 16:00, the *PGSV* glare value of the near section of Longquanshan No. 1 tunnel was 7.1017, far exceeding the unbearable glare limit. The corresponding difference of luminance contribution ratio outside the hole was as high as 94%. The *PGSV* for the road and surroundings after rainfall reached 3.0987 and 4.003, respectively, both exceeding the threshold of intolerable glare for drivers. It is not difficult to find that the glare effect after rain is very serious in the field of view outside the tunnel. At 16:00 p.m., the *PGSV* glare value in the access zone of Longquanshan No. 1 tunnel was 7.1017, far exceeding the unbearable glare limit. Compared with the glare value in normal weather, the glare value in the condition after rainfall is larger. Therefore, it was found that the glare phenomenon is more serious in the condition after rain than in the condition under normal sunshine. If this situation occurs in the morning (afternoon) on the road surface of the tunnel facing due east (due west), the uncomfortable glare will be more serious, affecting the safety and comfort of driving in the access zone of the tunnel.

Reference [29] suggests that a reasonable light distribution at the tunnel entrance has an impact on the driver’s perception of brightness and glare issues. During the day, the sunlight shines directly in the direction of the driver’s entry into the tunnel. Moreover, there is a significant difference in illumination between sunlight and tunnel lighting, which can cause problems and seriously interfere with the driver’s vision [30]. Disability glare is caused by improper luminance distribution, excessive luminance variation, or excessive contrast, resulting in a decrease in the ability to see important objects clearly. Mehri pointed out that disabling glare reduces the contrast of obstacles on the road, lowers safety levels, and leads to a significant increase in traffic accidents. Therefore, the author believes that in the access zone of the tunnel, the luminance difference inside and outside the tunnel should be minimized to reduce the human eye’s dark adaptation time [4], so that the driver has good visual adaptability when entering the tunnel. Similarly, for the generation of glare at the scene, the following specific measures can be taken. First, in response to the landscape factors outside the tunnel, dark vegetation can be planted outside the tunnel [31], and anti-glare buildings can be constructed [32,33] (such as pergola and tunnel sunshades) to reduce the luminance of the surroundings outside the tunnel, thereby reducing the difference in luminance between the inside and outside of the tunnel. These methods will reduce glare values. Second, in response to the road surface factors outside the tunnel, asphalt pavement or dark colored pavement should be laid on the road surface to reduce the contribution value of the road surface brightness near the tunnel entrance, slow down the luminance difference inside and outside the tunnel, and thus reduce the impact of uncomfortable glare on driving safety [34].

5. Conclusions

This study focuses on the glare phenomenon in the access zone of east–west oriented road tunnels and the time-varying characteristics of the $L_{20}(S)$ value of the luminance outside the tunnel. Through field tests, we analyzed the difference in luminance within and outside the tunnel. We focused on a 20° field of view from the human eye at a stopping sight distance from the tunnel entrance. The difference and time-varying characteristics between the measured and recommended values of luminance outside the tunnel were analyzed. The conclusions obtained are as follows:

(1) The time-varying characteristics of $L_{20}(S)$ in the access zone generally increase first and then decrease, and the maximum value of $L_{20}(S)$ in the east-oriented and west-oriented tunnels occurs at 11:00 a.m. and 14:00–16:00 p.m., respectively.

(2) The difference in the luminance of the contribution ratio outside and inside the tunnel is more than 95.7% in the morning (9:00 a.m.–11:00 a.m.), and the maximum is nearly 97%, while the difference in the luminance of the contribution ratio is smaller in the afternoon than in the morning. The contribution ratio of the luminance outside the road tunnel due west reaches the maximum at around 16:00 p.m. In addition, the luminance difference between the interior and exterior of the east–west oriented road tunnel generally increases first and then decreases.

(3) When the surroundings in the access zone of the east–west oriented road tunnel are subjected to direct sunlight, the visual environment presents an inappropriate luminance phenomenon due to the increased luminance difference between the inside and outside of the tunnel, resulting in uncomfortable glare and intolerable glare within the 20° field of view. And the situation will get worse after rainfall. If the glare problem is not controlled, it will affect driving safety and comfort.

(4) The test methods can serve as a reference for studying and designing visual environment quality, glare control, luminance $L_{20}(S)$ outside the tunnel and the surroundings of the tunnel. Simultaneously, the application of a 20° field of view and quantified indirect glare source research techniques pave the way for investigating the non-luminaire outside the tunnel glare and glare from other external structures.

(5) In the lighting design of the east–west oriented road tunnel, the impact of uncomfortable glare near the tunnel on the visual environment should be considered. It is advisable to select pavement materials with low reflectivity and arrange dark vegetation. This approach can reduce the brightness difference between the tunnel interior and exterior, enhancing driver safety and comfort.

Due to limitations in the experimental conditions, this experiment was unable to obtain very rich data. In the future, testing will be conducted under different weather conditions in spring, summer, autumn, and winter. In addition, the author plans to conduct research in areas with different altitudes and latitude in the future, exploring the impact of altitude and latitude on the brightness and glare issues outside the access zone of east–west oriented tunnels. For future work, the author is also considering establishing a model to evaluate the level of glare outside the tunnel.

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References

1. Statistical Communique on the Development of the Transportation Industry in 2022. Available online: https://www.gov.cn/govweb/lianbo/bumen/202306/content_6887539.htm (accessed on 21 June 2023).
2. Mehri, A.; Aliabadi, M.; Golmohammadi, R.; Zakerian, S.A. An empirical investigation of disability glare and visibility level during driving inside very long road tunnels: A case study. *Tunn. Undergr. Space Technol.* **2022**, *125*, 104496. [CrossRef]
3. Coco-Martín, R.M.; Cuadrado-Asensio, R.; Vega-Colado, C.; Vergaz, R.; Sánchez-Pena, J.M.; Viñuales, A.; Peris, S.; Artús, P.; Coco-Martín, M.B. Control of disability glare by means of electrochromic filtering glasses: A pilot study. *Tunn. Undergr. Space Technol.* **2017**, *10*, 1650028. [CrossRef]
4. Peña-García, A. Sustainable tunnel lighting: One decade of proposals, advances and open points. *Tunn. Undergr. Space Technol.* **2022**, *119*, 104227. [CrossRef]
5. Han, Z. Research on Highway Tunnel Lighting Demand Based on Equivalent Brightness. *China ITS J.* **2017**, *33*, 132–135.
6. Zhao, W.B.; Liu, Q.; Liu, S.R.; Wang, Q. Study on the time-varying characteristics of brightness outside the tunnel. *Highw. Traffic Technol.* **2017**, *33*, 132–135.
7. Huang, F.M. Experimental Research on Improvement Method of Highway Driver's Optical Illusion Based on "Black Hole Effect". Master's Thesis, Wuhan University of Technology, Wuhan, China, 2014.
8. Jin, S.C. Analysis and Simulation of the Effects of Highway Tunnel Lighting on Driver's Visual Glare. Master's Thesis, Chang'an Univercity, Xi'an, China, 2014.
9. Pan, B.B.; Weng, J. Review of research on light reduction measures for highway tunnel openings. *Lamps Light.* **2013**, *37*, 18–23.
10. Yuan, L.; Lu, J.; Zhu, L.L.; Xiang, Q.J. Research on Evaluation Index System and Evaluation Method of Expressway Greening. *J. Highw. Transp. Res. Dev.* **2007**, *24*, 150–153.
11. Ai, J.; Yang, B.L.; Li, Y.P. Design of light reduction and anti-glare at tunnel exit. *Tunn. Constr.* **2009**, *29*, 57–60.
12. Xu, Y.; Zheng, X.; Hu, Y.Q.; Li, X.; Liu, H.X. Quantitative evaluation of the discomfort glare of a tunnel pergola. *Tunn. Undergr. Space Technol.* **2020**, *95*, 103161. [CrossRef]
13. Yang, S.W.; Wang, Y.Z.; Pan, B.H. Calculating method of height of anti-glare plant in central partition. *J. Chang. Univ. Nat. Sci. Ed.* **2015**, *35*, 27–31.
14. Xiao, Y.; Du, Z.G.; Tao, P.P.; Wang, M.N. Study on the Improvement Method of "White Hole" Effect at the Exit of Highway Tunnels. *J. Wuhan Univ. Technol. Transp. Sci. Eng. Ed.* **2015**, *39*, 573–576.
15. CIE Publication 88. *Guide for the Lighting of Road Tunnels and Underpasses*; CIE Publication 88; Commission Internationale de l"Éclairage: Vienna, Austria, 2004.
16. Zhou, Y.; Zhao, B.; Tu, Y.; Shi, L.N. Quantitative Research on the Brightness L_{20}(S) Outside the Tunnel Based on Lighting Optimization. *Technol. Highw. Transp.* **2014**, *4*, 127–131.
17. Wei, T.; Gu, F.B.; Qian, F.; Cai, Y.; Chen, H.C. Overview of glare evaluation and prevention of LED lamps. *China Light Light.* **2015**, *7*, 32–35.
18. Bourdy, C.; Chiron, A.; Cottin, C.; Monot, A. Visibility at a tunnel entrance: Effect of temporal adaptation. *Light. Res. Technol.* **1987**, *19*, 35–44. [CrossRef]
19. Shunsuke, K.; Miyoshi, A.; Michico, I.; Nobuhiro, K.; Toshihiro, T. Study on evaluation of LED lighting glare in pedestrian zones. *J. Light Vis. Environ.* **2015**, *39*, 15–25.
20. Lin, Y.D.; Qiu, J.J.; Liu, Y.H. Rsearch Status and Development on Discomfort Glare. *China Illum. Eng. J.* **2016**, *27*, 7–13.
21. *JTG/T D70/2-01-2014*; Guidelines for Design of Lighting of Highway Tunnel. Ministry of Transport of the People's Republic of China: Beijing, China, 2014.
22. Qu, Z.H.; Zhao, Q.B.; Liu, X.H. Tunnel Ambient Exterior Luminance L_{20}(S) Tested by Environmental Sketch Method. *Technol. Highw. Transp.* **2004**, *5*, 117–121.
23. *JTJ 026.1-1999*; Specifications for Design of Ventilation and Lighting of Highway Tunnel. Ministry of Transport of the People's Republic of China: Beijing, China, 1999.
24. *GB 50034-2013*; Standard for Lighting Design of Buildings. Ministry of Housing and Urban-Rural Development of the People's Republic of China: Beijing, China, 2013.
25. Hopkinson, R.G. Glare from daylighting in buildings. *Appl. Ergon.* **1972**, *3*, 206–215. [CrossRef]
26. Iwata, T.; Tokura, M. Examination of the limitations of predicted glare sensation vote (PGSV) as a glare index for a large source: Towards a comprehensive development of discomfort glare evaluation. *Light. Res. Technol.* **1998**, *30*, 81–88. [CrossRef]
27. Boyce, P.R. *Human Factors in Lighting*, 3rd ed.; CRC Press: London, UK, 2003.

28. Iwata, T.; Taniguchi, T.; Sakuma, R. Automated blind control based on glare prevention with dimmable light in open-plan offices. *Build. Environ.* **2017**, *113*, 232–246. [CrossRef]
29. Chiradeja, P.; Yoomak, S. Optimal tunnel lighting design in aspect of lighting quality and energy performance. *Tunn. Undergr. Space Technol.* **2023**, *131*, 104837. [CrossRef]
30. Zhang, F.; Lu, J.; Hu, X.; Hao, X.T. Investigating safety impact of sun glare in urban tunnels based on cellular automata approach. *Accid. Anal. Prev.* **2020**, *148*, 105821. [CrossRef] [PubMed]
31. Peña-García, A.; López, J.C.; Grindlay, A.L. Decrease of energy demands of lighting installations in road tunnels based in the forestation of portal surroundings with climbing plants. *Tunn. Undergr. Space Technol.* **2015**, *46*, 111–115. [CrossRef]
32. Gil-Martín, L.M.; Gómez-Guzmán, A.; Peña-García, A. Use of diffusers materials to improve the homogeneity of sunlight under pergolas installed in road tunnels portals for energy savings. *Tunn. Undergr. Space Technol.* **2015**, *48*, 123–128. [CrossRef]
33. Peña-García, A.; Gil-Martín, L.M. Study of pergolas for energy savings in road tunnels. Comparison with tension structures. *Tunn. Undergr. Space Technol.* **2013**, *35*, 172–177. [CrossRef]
34. Cantisani, G.; D'Andrea, A.; Moretti, L. Natural lighting of road pre-tunnels: A methodology to assess the luminance on the pavement–Part II. *Tunn. Undergr. Space Technol.* **2018**, *73*, 170–178. [CrossRef]