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Simulation Analysis of an ETC Monitoring and Imaging Supplementary Lighting Device for Freeways

Shijian Yin [1,2], Zhiyong Ma [2], Xiaojie Luo [3] and Huayang Yu [2,*]

1 Erguang Branch of Guangdong Road & Bridge Construction Development Co., Ltd., Guangzhou 510000, China; yinshijian@lqfssc.com

2 School of Civil Engineering and Transportation, South China University of Technology, Guangzhou 510000, China; 202421009850@mail.scut.edu.cn

3 Guangdong Communication Planning & Design Institute Group Co., Ltd., Guangzhou 510000, China; luoxioajie@ghdi.cn

* Correspondence: huayangyu@scut.edu.cn; Tel.: +86-188-9883-7614

Abstract: To address the glare issues caused by highway ETC gantry monitoring and imaging illumination devices, this paper first investigates the mechanism of disability glare and derives the formula for the glare threshold increment. Subsequently, using the glare increment threshold as the evaluation metric and incorporating the current regulatory requirements for illumination devices, a simulation model for ETC gantry monitoring and imaging illumination devices was developed. A single-variable control method was applied to conduct simulation experiments on the glare problems from multiple perspectives (e.g., different standard illuminance levels, various luminous areas, varying installation heights, and different lateral offsets), and the glare level was analyzed using the glare increment threshold method. It was found that when the lateral offset of the illumination device reached 4 m, the glare increment threshold decreased by more than 50%. Additionally, it is recommended that the illuminance of the illumination device should be greater than 15 lx.

Keywords: highway; glare; modeling simulation; supplementary lighting device; ETC gantry

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Academic Editor: António Couto

Received: 6 November 2024

Revised: 16 December 2024

Accepted: 29 December 2024

Published: 14 January 2025

Citation: Yin, S.; Ma, Z.; Luo, X.; Yu, H. Simulation Analysis of an ETC Monitoring and Imaging Supplementary Lighting Device for Freeways. *Infrastructures* **2025**, *10*, 19. https://doi.org/10.3390/infrastructures10010019

1. Introduction

In recent years, with the continuous improvement in China's road traffic network and the rapid growth in the number of privately owned motor vehicles, the issue between road traffic conditions and driving safety has become increasingly acute. According to data released by the National Bureau of Statistics, there were as many as 240,000 traffic accidents in China in 2020 [1], of which 70% were caused by human factors. Additionally, the fatality rate for night-time traffic accidents is twice that of daytime accidents [2,3]. Among the many influencing factors, changes in the road lighting environment are a significant contributor to traffic accidents. Currently, the electronic toll collection (ETC) system is widely adopted and applied to highways in China. To ensure the reliability of the cameras in ETC gantries under poor lighting conditions, such as during night-time, and to provide law enforcement with accurate data for post-enforcement activities, the ETC gantry system is equipped with lighting devices that provide supplemental illumination via pulse or continuous lighting modes. Although these measures significantly enhance the quality of the cameras' evidence capture, the high-intensity light emitted by the supplemental lighting devices also causes glare, which interferes with drivers' vision [4,5]. Therefore, it is necessary to conduct an in-depth study on the glare issue caused by the supplemental lighting devices of the ETC gantry system.

A series of studies have addressed the issue of glare caused by road traffic lighting environments. Some research specifically focuses on the glare experienced by drivers within tunnels [6–15], some studies focus on the glare experienced by elderly drivers on the road [16–26], and some studies have used various methods, such as model simulations, laboratory experiments, and field tests, to investigate road glare under different traffic scenarios, providing valuable references for road glare research. Ketvirtis discussed disability glare in high-mast lighting design and outlined key issues in improving high-mast lighting systems [27]. Jiayin Song et al. constructed parameters for three typical overpass models and conducted subjective evaluations using the semantic differential method [28], proposing evaluation indicators and thresholds for disability glare on overpass roads in China. Huang Lei et al. conducted indoor simulations and field tests of glare, analyzing it from three dimensions [29]: the installation setup of the supplemental lighting device, the type of light source, and the supplemental lighting distance. They proposed three methods for effectively controlling the glare caused by the supplemental lighting device. Through glare effect experiments, Jiangbi Hu et al. determined the illuminance thresholds and spatial distribution for various levels of glare [30]. Michael Sivak et al., through field experiments [31], investigated the impact of age and ambient glare on the night-time legibility of traffic signs. H.-J. Schmidt-Clausen et al. conducted experimental research on discomfort glare in vehicle lighting using a proportional model and derived a formula suitable for calculating discomfort glare [32]. Wei Ting et al. analyzed the glare evaluation factors of LED lamps [33], pointed out the shortcomings of the current common glare evaluation systems, and proposed corresponding improvement suggestions. Bian Yanni et al. measured and analyzed the illuminance data of supplemental lights during actual operation [34] and proposed three specific measures to reduce glare caused by supplemental lights for drivers. In these studies, equivalent veiling luminance and glare increment threshold were given significant attention. Equivalent veiling luminance primarily describes the effect of a single glare source on the human, while the glare increment threshold is used to evaluate the impact of glare sources in a lighting environment.

Currently, there are relatively few studies in China specifically addressing the glare issues caused by supplemental lighting devices in ETC systems. Although the Ministry of Public Security issued a series of technical standards around 2014, such as " General technical specifications for fill light devices of traffic monitoring cameras (GA/T1202-2014)" [35], "Technical specifications for automatic recognition technology of motor vehicle license plate images (GA/T833-2016)" [36], and "General technical conditions of automatic recording system for illegal parking of motor vehicles (GA/T1426-2017)" [37], these standards only provide requirements on aspects such as average illuminance and peak illuminance of supplemental lighting devices. They are insufficient in addressing specific visual stimulus limitations, as seen in regulations like the "Technical Requirements for Highway Lighting" and the "Design Standards for Urban Road Lighting" [38], and there are no clear specifications on the minimum illuminance required for night-time license plate recognition. During freeway inspection and acceptance stages, there are currently no direct methods or indicators available for on-site testing or glare control of ETC gantry supplemental lighting devices during the construction phase. Additionally, there is a lack of clear quantitative acceptance standards for these devices after project completion, resulting in inconsistent lighting effects and intensity levels across different projects, which has become a weakness in project acceptance.

This paper explores the mechanism by which ETC gantry monitoring and imaging supplementary lighting devices affect drivers' visual responses. Using DIALux 4.13 simulation software, a model of the ETC monitoring and imaging supplementary lighting device was established. Under the condition of meeting the regulatory requirements for license plate recognition accuracy, a multi-dimensional simulation analysis of the glare issues caused by the device was conducted. Effective measures to mitigate the visual disturbance caused by the ETC gantry lighting device were proposed. The experiments aim to further improve current regulations by addressing gaps in glare level classification and glare limitation standards for ETC systems on highways, providing practical guidance for project implementation and acceptance testing.

2. The Mechanism and Evaluation Metrics of Disability Glare

On highways, the primary reason for the poor imaging quality of ETC gantry surveillance cameras is the excessive brightness contrast between the vehicle's license plate area and the surrounding environment. In some cases, certain road sections lack lighting infrastructure, resulting in significant losses in road surface illumination during night-time or under low-light conditions such as cloudy or stormy weather. This fails to meet the minimum illumination required for the ETC gantry cameras to recognize license plates. In other cases, the excessive brightness of headlights during night-time driving leads to overexposure in the headlight area or underexposure in the license plate area, causing the camera to capture images with insufficient or excessive film density, thus affecting the clarity of the ETC gantry camera's imaging. Therefore, given the specific environmental conditions and scenarios of highways, appropriate supplementary lighting must be installed to ensure the imaging quality of ETC gantry cameras. However, this inevitably causes disability glare to drivers. To mitigate the visual disturbances caused by the supplementary lighting and to enhance road safety, it is essential to first understand the mechanism behind disability glare.

2.1. Equivalent Veiling Luminance

Glare refers to a temporary or even long-term visual impairment experienced by an observer when the surface luminance of an object is too high or when there is a significant luminance difference between the object and its surrounding environment, thus reducing the observer's ability to perceive and interpret the object [39,40]. Generally, based on different visual perceptions, the impact of a glaring light source on an observer can be classified into discomfort glare and disability glare [41–43]. Discomfort glare primarily refers to the visual discomfort caused by a glaring light source, which may intensify as the strength or duration of the light increases [44]. However, this type of glare does not necessarily reduce the observer's ability to recognize the shape or characteristics of the target object [45]. Research on discomfort glare is primarily based on subjective response tests and mainly uses the de Boer rating scale for subjective assessment [46,47]. Disability glare occurs when the light from a glaring source creates a visual effect in the observer's field of vision, overlapping with the image of the target object, thereby significantly impairing the observer's ability to perceive the object [48–50].

Figure 1 illustrates the formation mechanism of disability glare. Assuming that the observer's eye C has already focused the information of target object B onto the retina, the high-intensity light from glare source A enters the observer's eye C. Some of the light scatters due to the refractive medium inside the eyeball, overlaying an uneven luminance layer onto the retina, known as the equivalent veiling luminance L_v [51–53].

From the perspective of the observer, in order to obtain a clear image of the target object in the field of view, it is necessary to give the target object a certain brightness contrast. Assuming that the brightness of the target object is L_0, the brightness of the background is L_b, then the brightness contrast without glare C_0 can be expressed as follows:

$$C_0 = |L_0 - L_b| / L_b. \tag{1}$$

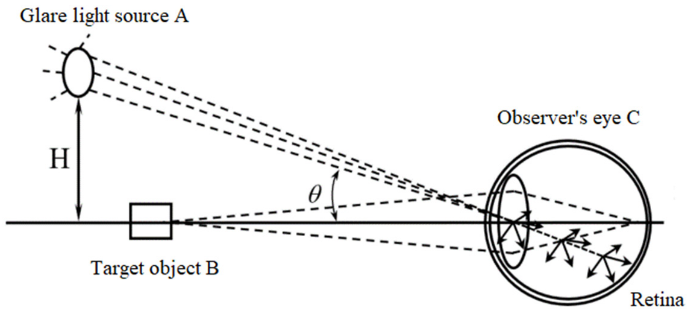

Figure 1. The formation mechanism of disability glare.

Under the action of the glare light source, due to the existence of the equivalent veiling luminance being L_v, the effective brightness contrast of the target object C_{eff} can be expressed as follows:

$$C_{eff} = |(L_0 + L_v) - (L_b + L_v)|/(L_b + L_v). \quad (2)$$

Combining Formulas (1) and (2), the relationship between C_{eff} and C_0 can be obtained as follows:

$$C_{eff} = C_0 \cdot L_b/(L_b + L_v). \quad (3)$$

For freeway scenes, when the ETC gantry light supplement device works, it is equivalent to adding a glare light source to the driver's field of vision. Compared with the background brightness contrast of the target object under the non-glare light source in Formula (1), in Formula (2), the presence of a glare source creates an equivalent veiling luminance, L_v, on the retina, which reduces the effective brightness contrast, C_{eff}, of target objects in the driver's field of view, thereby impairing the driver's visual ability, as shown in Formula (3). Thus, the magnitude of the equivalent veiling luminance L_v formed on the retina is one of the key factors determining the occurrence of disability glare for drivers. This is also consistent with previous research.

After conducting research on the causes of glare, Holladay innovatively proposed two main factors influencing the equivalent veiling luminance: (1) the angle θ between the light emitted from the glare source entering the observer's eye C and the line of sight from the observer's eye C to the target object B, and (2) the vertical illuminance L_v formed by the glare source within the observer's eye C [42]. Later, through development and refinement by scholars such as Fisher, Hartmann, and Adrian [54–56], a classic formula for calculating the equivalent veiling luminance was derived:

$$L_v = k \sum \frac{E_{eye}}{\theta^n}. \quad (4)$$

In the formula, k represents a ratio constant related to the target size and observation time, and n represents a constant related to the optical structure of the eye. Further research by Fisher and Christie demonstrated that the value of k is influenced by the observer's age and brightness distribution within the field of view [55]; additionally, Watson found that k and n depend on variations in θ [57]. Although the Holladay–Stiles formula is not entirely precise, it is generally considered to provide a reasonable description of the disability glare effect.

2.2. Effective Field of View Angle Glare Threshold Increment

While driving on highways, a driver's forward field of view is somewhat limited due to obstructions such as the car window and roof. Previous studies have found that increasing the angle between the glare source and the driver's visual center can achieve the effect of reducing the glare source's brightness [58,59]. Therefore, the effective visual field angle is also a key factor in determining disability glare. As shown in Figure 2, which illustrates the relationship between the glare source and the driver's visual center, the size of the effective field of view angle θ depends on the distance d between the driver's visual center C and the point of focus B, as well as the height of driver's visual center h. Assuming the glare source A is located at a height of H, and the horizontal distance between the driver's visual center C and glare source A is L, the formula for calculating θ can be expressed as follows:

$$\theta = \alpha_1 + \alpha_2 = \tan^{-1}\frac{H-h}{L} + \tan^{-1}\frac{h}{d}. \quad (5)$$

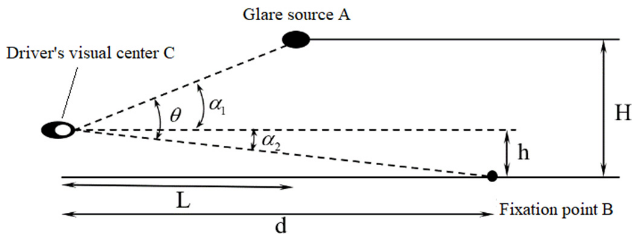

Figure 2. Schematic diagram of the relationship between light complement devices and the driver's vision.

The presence of equivalent veiling luminance L_v reduces the clarity and contrast of the image of the target on the retina, thereby weakening the driver's visual perception [60]. Research has shown that the brightness contrast between the target object and its background has a greater impact on human vision, perception, and response [49,61]. This brightness difference depends not only on the glare source's brightness but also on the brightness of the remaining areas within the visual field [43,62]. Based on the CIE "Standards for Urban Road Lighting Design" and the "Requirements of optical radiation safety for active lighting units of video surveillance systems" regarding disability glare evaluation parameters [63,64], this paper uses the glare increment threshold TI to evaluate the disability glare of ETC gantry monitoring illumination devices on highways [65].

As a metric for disability glare, TI refers to the percentage increase in brightness contrast between the target object and its background required to restore normal viewing conditions [66,67]. Under normal conditions, the average road surface brightness in China L_{av} $(\text{cd} \cdot \text{m}^{-2})$ meets the condition for $0.05 < L_{av} < 5$; thus, the formula for calculating TI can be expressed as follows:

$$TI = 65 \times \frac{L_{vt}}{L_{av}^{0.8}}(\%). \quad (6)$$

In the formula, L_{vt} represents the sum of generated L_v by all glare sources within the observer's field of view. Combining Formulas (4)–(6) can be rewritten as follows:

$$TI = 65 \times \frac{L_{vt}}{L_{av}^{0.8}}(\%) = \frac{65}{L_{vt}} \times k \times \sum \frac{E_{eye}}{\tan^{-1}\frac{H-h}{L} + \tan^{-1}\frac{h}{d}}(\%). \quad (7)$$

In this formula, the value of the k constant depends on the driver's age. Assuming A represents the observer's age, k can be expressed as follows:

$$k = 9.86 \times \left[1 + \left(\frac{A}{66.4}\right)^4\right]. \quad (8)$$

Currently, when applying Formula (7) to calculate and verify disability glare, the value of k is generally based on the recommendation from the 9th CIE Congress. The observer, aged 23 years old, is taken as the research object; therefore, k = 10, and n should be valued as 2 [68].

3. Construction of the Simulation Model for the ETC Gantry Supplementary Lighting Device

Figure 3 shows the simulated scene of the standardized simulation model built for this study. The angle between the light emitted by the ETC gantry supplementary lighting device and the line of sight from the driver's visual center to the target object primarily depends on the installation height and offset distance of the supplementary light. The increment of the glare threshold TI formed by the supplementary light in the driver's visual center is mainly related to the luminous area, illuminance, and ambient brightness of the supplementary device [69]. The environmental brightness of the standard model is set to 0.5 $cd \cdot m^{-2}$; the lighting area of the supplemental lighting device is set to 50 cm^2, and it is installed at a vertical height of 6.5 m above the lane. The installation angle of the supplemental light source directly faces the vehicles, with the central illuminance focused on the middle of the lane at a distance of 25 m. For the parameter settings of the lighting illuminance of the supplemental device, the principle used in the experiment is that the front illuminance should reach 40 lx at a distance of 20 m from the ETC gantry. Assuming the observer's eye is located at the left quarter of the lane, at a height of 1.5 m (with the lower edge of the observation plane 1.5 m above the ground, with a height of 10 cm and a width of 30 cm), and the license plate is positioned in the center of the lane at a height of 0.5 m (with the lower edge of the observation plane 0.5 m above the ground, with a height of 10 cm and a width of 30 cm), the distance between the observation plane and the supplemental lighting device can be adjusted, and combined with Formula (4), the TI value of the supplemental lighting device under different parameter conditions can be tested and calculated. In Figure 3, a refers to the location of the vehicle license plate at a height of 0.5 m, and b refers to the location of the driver's visual center at a height of 1.5 m.

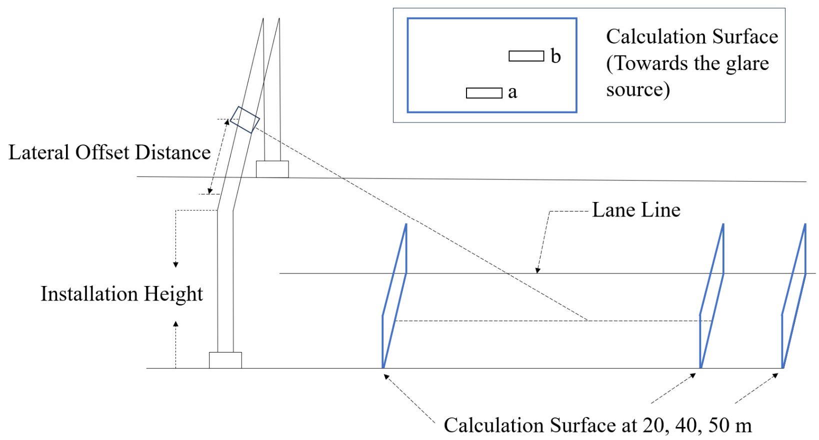

Figure 3. Schematic diagram of the simulation model.

4. Simulation Results Analysis

4.1. Ambient Luminance

To better analyze the glare problem of the ETC monitoring and imaging supplemental lighting device, this section models and simulates four environmental brightness values: 0.05 $cd{\cdot}m^{-2}$, 0.5 $cd{\cdot}m^{-2}$, 1 $cd{\cdot}m^{-2}$, and 2 $cd{\cdot}m^{-2}$. The data obtained are shown in Table 1.

Table 1. Glare increment threshold TI under different ambient brightness conditions.

Ambient Brightness ($cd\cdot m^{-2}$)	TI Values of Observation Surfaces at Different Positions (%)		
	25 m	40 m	50 m
0.05	1244	286	131
0.5	197	45	21
1	113	26	12
2	65	15	7

From Table 1, it can be seen that as the distance between the driver and the supplemental lighting device changes from 50 m to 25 m, the TI value also increases significantly. When the environmental brightness remains at 0.5 $cd\cdot m^{-2}$, compared with the TI values measured at 40 m and 50 m, the TI value at 25 m sharply increases from 45% and 21% to 197%. When keeping the brightness of the monitoring imaging light supplement device unchanged and changing the set value of the ambient brightness, the degree of the driver's vision affected by the light supplement device will become more and more serious with the decrease in the ambient brightness value. For example, at a distance of 25 m, when the environmental brightness is 0.05 $cd\cdot m^{-2}$, the glare increment threshold reaches 1244%, which is approximately 5.3 times higher than 197% when the environmental brightness is 0.5 $cd\cdot m^{-2}$. Compared with the 65% value at an environmental brightness of 2 $cd\cdot m^{-2}$, the TI value at 0.05 is approximately 18 times higher.

4.2. Lamp Luminous Area

This section uses a reference distance of 25 m from the supplemental lighting device, keeping the illuminance and TI value at 25 m unchanged. The lighting area of the lamps is set at 50 cm^2, 100 cm^2, 200 cm^2, and 500 cm^2 for modeling tests. The experimental results are shown in Table 2. However, this influencing factor does not account for the impact of the luminous area on the driver's visual stimulation. For instance, when the luminous area of the lamp is adjusted from 50 cm^2 to 500 cm^2, considering only the effect of brightness is insufficient. Future research should specifically determine the degree of visual stimulation experienced by drivers when the luminous area changes.

Table 2. Glare increment threshold under different luminaire area conditions.

25 m Illuminance (lx)		TI (%)	Lamp Aera (cm^2)	Lamp Brightness ($cd\cdot m^{-2}$)
0.5 m	1.5 m			
35	37	197	50	402
			100	201
			200	100
			500	40

It can be seen that when the TI value at 25 m is maintained at 197%, reducing the brightness of the supplemental lighting device can be achieved by changing the luminous area. When the lamp's luminous area is adjusted from 50 cm^2 to 500 cm^2, the required brightness of the lamp decreases from 402 ($cd\cdot m^{-2}$) to 40 ($cd\cdot m^{-2}$), showing an inverse proportional relationship. Although changing the lamp's luminous area has no impact on the TI value, increasing the lighting area will reduce the brightness of the lamp, thereby lowering the disability glare perceived by the driver when directly looking at the supplemental lighting device.

4.3. Luminance of Supplementary Lighting Devices

This section selects the standard illuminance at 20 m as a control variable and constructs four simulation scenarios with illuminance values of 10 lx, 20 lx, 30 lx, and 40 lx at 20 m. The illuminance values of observation surfaces at 25 m, 40 m, and 50 m at different heights are measured, and the experimental data are shown in Table 3. The data show that as the standard illuminance of the supplemental lighting device increases from 10 lx to 40 lx, the values at the three positions increase to varying degrees. For example, at the 25 m observation point, the TI value at 20 lx is 75%, which is more than double 37% at 10 lx. At 30 lx and 40 lx, the TI values reach 149% and 197%, respectively, which are 3–4 times higher than the TI value at 10 lx.

Table 3. Glare increment threshold under different standard illuminance conditions.

Standard Illuminance of Lamp at 20 m (lx)		**10**	**20**	**30**	**40**
25 m illuminance (lx)	0.5 m	7	13	26	35
	1.5 m	7	14	28	37
TI value at 25 m (%)		37	75	149	197
40 m illuminance (lx)	0.5 m	2.1	4.2	8.5	11
	1.5 m	1.6	3.2	6.4	8.5
TI value at 40 m (%)		8	17	34	45
50 m illuminance (lx)	0.5 m	1	1.9	3.9	5.2
	1.5 m	0.7	1.4	2.9	3.9
TI value at 50 m (%)		4	8	16	21

To meet the illumination requirements for vehicle license plate recognition, the illuminance at the license plate position (0.5 m height) 40 m away from the ETC gantry should not be less than 3 lx. In Table 3, a linear fit was performed on the data for the position 40 m away at a height of 0.5 m. As shown in Figure 4, considering the limited number of data, a first-order linear function was used for the fit. Taking the standard illuminance as the independent variable, the fitted function is $y = 0.31x - 1.3$, with a correlation coefficient of 0.98, indicating a good correlation. Through calculations, when the illuminance at 40 m is not less than 3 lx, the standard illuminance should be no less than 13.8 lx. Therefore, to ensure the accuracy of photographic recognition, the average illuminance should be greater than or equal to 15 lx.

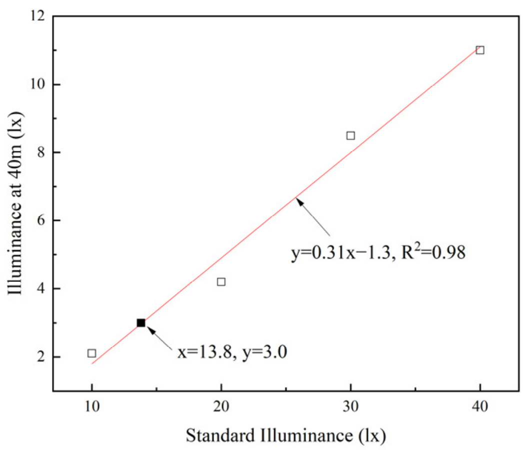

Figure 4. Univariate function fitting graph of standard illuminance and illuminance at 40 m.

4.4. Installation Height of Supplementary Lighting Devices

To ensure safe vehicle passage, the ETC gantry must have a sufficient installation height. Based on this, this section takes the installation height of the supplemental lighting device as a control variable, constructing three simulation scenarios with heights of 6.5 m, 7.5 m, and 8.5 m, and measuring the illuminance values of observation surfaces at 25 m, 40 m, and 50 m. The data in Table 4 show that as the installation height of the device increases, the spatial angle also increases, which indirectly affects the angle between the glare source and the observer's line of sight, resulting in a significant decrease in the TI value. For example, at the 40 m observation point, when the device is installed at 6.5 m, the observer's eye illuminance is 8.5 lx, with a corresponding TI value of 45%. When the installation height is increased to 7.5 m and 8.5 m, the illuminance decreases to 7.03 lx and 4 lx, and the corresponding TI values drop significantly to 29% and 13%, respectively.

Table 4. Glare increment threshold under different installation height conditions.

Mounting Height (m)		**6.5**	**7.5**	**8.5**
Installation Space Angle (°)		**14.6**	**16.7**	**18.8**
25 m illuminance (lx)	0.5 m	35	35	33
	1.5 m	37	37	28
TI value at 25 m (%)		197	150	90
40 m illuminance (lx)	0.5 m	11	9.62	5.51
	1.5 m	8.5	7.03	4
TI value at 40 m (%)		45	29	13
50 m illuminance (lx)	0.5 m	5.2	3.9	2.1
	1.5 m	3.98	3	1.2
TI value at 50 m (%)		2.25	1.71	0.5

4.5. Lateral Offset Distance of Supplementary Lighting Devices

Existing ETC monitoring and imaging supplemental lighting devices are usually installed directly facing the lane, which increases the disability glare of drivers when looking directly at the device and extends the time during which the driver's vision is disturbed by the strong light. Therefore, this section takes the lateral offset distance of the lighting device as a control variable, simulating four offset distances: 0 m, 2 m, 4 m, and 6 m. The simulation results are recorded in Table 5. From Table 5, it can be seen that for any observation point, changing the lateral offset distance has little effect on the illuminance at that point but causes varying degrees of change in the TI value. For example, at the 40 m observation point, when the device is directly facing the lane (lateral offset 0 m), the illuminance at the observer's eye is 8.5 lx, with a corresponding TI value of 45%. When the device is laterally offset by 2 m, the illuminance changes little, but the TI value decreases from 45% to 40%. When the offset is 4 m and 6 m, the illuminance changes slightly compared to no offset, with a difference of about 6 lx, but the TI value significantly drops from 45% to 22% and 13%, a reduction of over 50%.

Figure 5 shows the simulated light patterns for different lateral offset distances. It can be seen that regardless of whether the lighting device faces the lane directly or is offset laterally, the central brightness remains concentrated near the center line of the two lanes, indicating that applying a certain lateral offset does not affect the lighting performance or the quality of supplemental lighting for the monitored area.

Table 5. Glare increment threshold TI under different lateral offset distance conditions.

Lateral Offset Distance (m)		**0**	**2**	**4**	**6**
Installation Space Angle (°)		**14.6**	**15.2**	**17**	**19.5**
illuminance at 25 m (lx)	0.5 m	35	35	36	36
	1.5 m	37	37	39	39
TI value at 25 m (%)		197	181	153	116
illuminance at 40 m (lx)	0.5 m	11	12	8	6
	1.5 m	8.5	8	6	4
TI value at 40 m (%)		45	40	22	13
illuminance at 50 m (lx)	0.5 m	5.2	5	3	2
	1.5 m	3.9	4	2	2
TI value at 50 m (%)		21	18	9	5

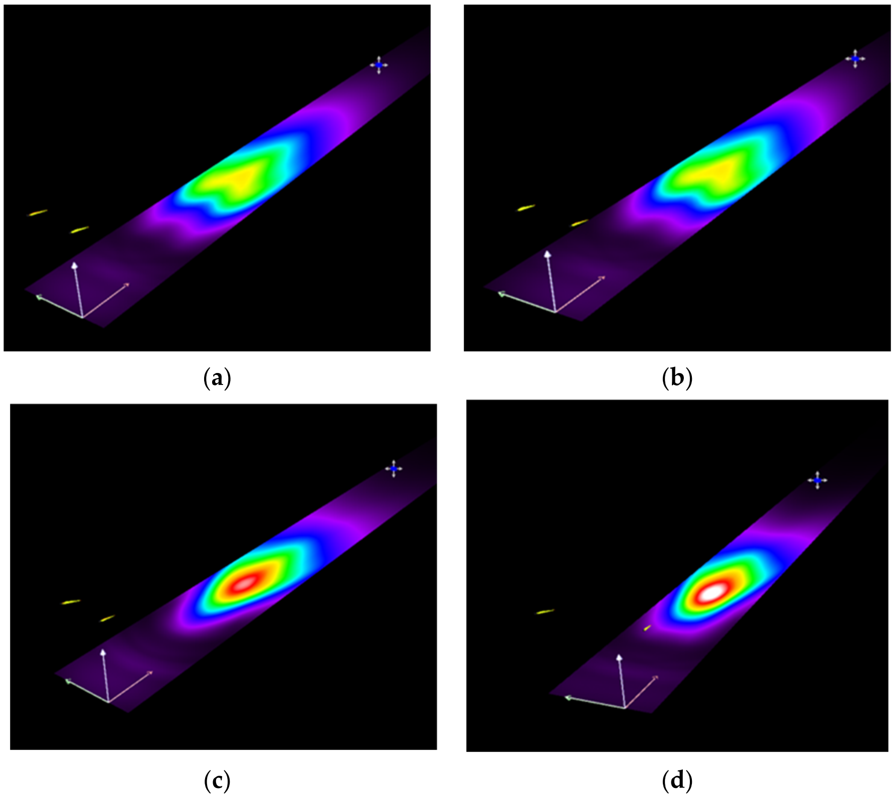

Figure 5. Simulated spot patterns in scenes with different lateral offset distances. (**a**) The lateral offset of the light supplement device is 0 m. (**b**) The lateral offset of the light supplement device is 2 m. (**c**) The lateral offset of the light supplement device is 4 m. (**d**) The lateral offset of the light supplement device is 6 m.

5. Discussion

This study aims to address the glare issue caused by ETC supplementary lighting devices on highways. Although earlier studies have extensively discussed disability glare, specifically caused by ETC supplementary lighting devices, their optimal parameter settings have not been thoroughly explored. Using a simulation model built with DIALux 4.13 software, we found that adjusting the lateral offset distance of the device to 4 m can reduce the glare increment threshold by 50%, and it does not compromise the supplementary lighting quality in the monitoring area. Additionally, to ensure the accuracy of vehicle license plate recognition, data fitting was performed, revealing that the supplementary lighting illuminance at 20 m should not be less than 15 lx when R^2 is 0.98.

These results confirm that optimizing the parameters of ETC supplementary lighting devices can significantly reduce the glare increment threshold while ensuring license plate recognition accuracy. This alleviates the issue of impaired driver vision caused by excessive brightness from the supplementary lighting devices. These findings suggest that using model evaluations to analyze glare problems in specific scenarios is an effective approach for studying driver glare issues. Most studies have focused on simulating and analyzing real-world glare scenarios; however, subjectivity in testers' evaluations can introduce certain errors. Therefore, combining model simulations with subjective evaluations in future research presents a viable method for analyzing glare issues. This study explored glare problems through model analysis, but field measurements are still required to validate the model's effectiveness. Furthermore, the relative impacts of various factors need to be further quantified to determine the most effective mitigation strategies, which are essential for resolving the glare issues caused by supplementary lighting devices in practice. Moreover, the disability glare model developed in this study is based on a static system and cannot fully simulate the dynamic visual system of drivers. Consequently, future research will focus on modeling dynamic disability glare and further exploring additional optimization strategies for supplementary lighting devices.

With the rapid proliferation of ETC systems on highways, the issue of disability glare caused by supplementary lighting devices cannot be overlooked. Existing standards that address average and peak illuminance levels for these devices are insufficient. The primary issue lies in the lack of specific restrictions on visual stimuli and the absence of further requirements for minimum supplementary lighting illuminance at night to ensure license plate recognition accuracy. In the inspection and acceptance phases of ETC supplementary lighting devices, there is currently a lack of on-site testing or glare control metrics during the construction stage, as well as quantitative acceptance standards post-completion. After project completion, the performance and intensity indicators of supplementary lighting devices vary significantly, creating a weak link in project acceptance. Therefore, modeling and analyzing the disability glare of ETC supplementary lighting devices can provide guidance and reference for their implementation and acceptance in specific projects.

6. Conclusions

Through modeling simulation and quantitative analysis, this paper studied the glare problem caused by the ETC gantry monitoring imaging supplemental lighting device on drivers. Based on the established standard model, the paper explored optimization strategies for the device under different control variables. The main conclusions are as follows:

1. Increasing the lighting area of the device can reduce the disability glare on the driver and lower the power required by the device.
2. Increasing environmental brightness or reducing the standard illuminance of the device can effectively mitigate the glare problem.
3. The current industry standard, "General Technical Specifications for Fill Light Deices of Traffic Monitoring Cameras" [35], requires in article 4.3.1-3 that "the average illuminance should be less than or equal to 50 lx". Based on the experimental results, it can be further optimized to "the average illuminance should be less than 50 lx and greater than or equal to 15 lx".
4. Adjusting the installation angle or the lateral offset distance of the lighting device can effectively reduce the stimulation caused by strong light on the driver's vision. According to the simulation results, when the lateral offset is 4 m, the illuminance at 40 m is 8 lx, meeting the illuminance requirement for license plate recognition. Considering the ease of on-site implementation, it is recommended to adopt an offset

installation method for the supplemental lighting device (i.e., a lateral offset of 3.75 m and a spatial angle of approximately 16°).

Author Contributions: Conceptualization, S.Y. and H.Y.; methodology, S.Y., Z.M. and X.L.; validation, S.Y. and Z.M.; investigation, S.Y., Z.M. and X.L.; writing—original draft preparation, S.Y. and H.Y.; supervision, H.Y.; funding acquisition, H.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Natural Science Foundation of Guangdong Province, China (grant numbers 2023A1515030287 and 2022A1515011537).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank the technicians in the Road laboratories of the South China University of Technology for technical support and assistance in experimental activities.

Conflicts of Interest: Shijian Yin is employed by Erguang Branch of Guangdong Road & Bridge Construction Development Co., Ltd.; Xiaojie Luo is employed by Guangdong Communication Planning & Design Institute Group Co., Ltd. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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