

Article

Research on Road Lighting Control Strategies Based on the Impact of Different Lighting Sources on Driver Visibility

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Abstract

This study analyzes the characteristics of natural lighting and artificial lighting illuminance, correlated color temperature (CCT), and color rendering index (CRI), and their impact on driver visibility. A real-vehicle experiment was conducted to assess visual recognition distances for small targets under various lighting conditions: six levels of natural light illuminance, and artificial lighting combinations of four CCT levels (3000–6000 K) and five illuminance levels (7.5–67.5 lx). Regression models were developed to relate light source characteristics to visual recognition distance. At low speeds (40 km/h), the natural light illuminance thresholds for activating/deactivating road lighting match current standards. At higher speeds (60 km/h, 80 km/h, and 100 km/h), these thresholds increase significantly, reaching 2, 5.5, and 22 times the standard values, suggesting safety risks at speeds ≥ 60 km/h. The study also finds that visual recognition distance decreases and then increases with rising CCT, with a minimum at 4000 K and a maximum at 6000 K. At 6000 K, the required illuminance thresholds decrease by 52.32%, 47.74%, and 58.31% at 60 km/h, 80 km/h, and 100 km/h, respectively. The research findings provide a reference for optimizing road lighting control strategies, balancing road safety and energy efficiency.

Keywords: road lighting; natural lighting; artificial lighting; illuminance thresholds; visual recognition distance; control strategy

1. Introduction

A high-quality road lighting environment is a critical factor in ensuring road operational safety and efficient traffic capacity [1]. The limited illumination distance of the vehicle's headlights cannot fully meet the driver's nighttime visual recognition needs [2]. To address this deficiency, an increasing number of roads are being equipped with lighting facilities. Given the generally long mileage and high energy consumption of each lighting fixture in road lighting projects, their scale effect on energy consumption is significant [3]. In order to save energy while meeting traffic safety requirements, it is necessary to activate road lighting in a timely and reasonable manner when natural light levels are insufficient. When natural light conditions meet safe driving requirements, road lighting needs to be turned off to avoid lighting waste [4,5]. On the other hand, to achieve sustainable nighttime road lighting, LED light sources with high luminous efficacy and energy-saving characteristics are increasingly being applied in road lighting [6]. Compared to traditional lighting



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sources such as HPS lamps, LED light sources also offer advantages such as adjustable spectrum and the ability to create various correlated color temperatures (CCT) and color rendering index (CRI). Since current road lighting standards only specify luminance or illuminance but lack clear technical requirements for light source CCT and CRI, different roads can be set with varying lighting CCT and CRI based on needs [7]. In practice, the application of lighting CCT and CRI exhibits significant arbitrariness. As the number of roads with nighttime lighting increases, the differences in lighting CCT and CRI between roads are becoming increasingly noticeable to drivers' visual perception. Existing standards adopt a single lighting illuminance criterion, making it difficult to address the challenges posed by variations in road lighting CCT and CRI. When CCT and CRI change result in road illuminance falling below the visibility threshold, it may introduce driving safety hazards, while exceeding the threshold can lead to energy waste. Consequently, establishing an effective strategy for road lighting—ensuring that it satisfies drivers' safety and visual recognition needs while preventing energy waste—has become a critical issue in operational management.

To achieve timely and effective control of road lighting facilities, existing research has evolved from manual control to automatic control, and further to intelligent control [8,9]. Recent studies have focused on constructing road lighting control systems that encompass a perception layer, transmission layer, and control layer, enabling the activation/deactivation control and management of streetlights on individual roads and networks of multiple roads [10]. Specifically, the control layer, leveraging intelligent algorithms and preset rules, conducts in-depth processing and analysis of perceived and transmitted data, generates control commands, and subsequently adjusts the activation/deactivation status of road lighting. As the core of judgment and decision-making for road lighting activation/deactivation, rational preset rules, namely control strategies, are pivotal to ensuring the safe and energy-efficient operation of road lighting systems.

Research on activation/deactivation strategies for road lighting facilities is primarily divided into two categories: those based on time and those based on natural illuminance [11]. In studies using time as the judgment criterion, to enable the activation/deactivation of lighting facilities, researchers incorporate sunrise and sunset time calculation programs into road lighting control devices, implementing lighting control operations based on these calculated times [12,13]. However, relying solely on sunrise and sunset times as the basis for determining the activation/deactivation of road lighting facilities cannot ensure that the road light environment quality meets drivers' visual recognition requirements for safe driving, thus presenting significant limitations. In standards and research using natural illuminance as the judgment criterion, China's Standard for Lighting Design of Urban Road (CJJ 45-2015) specifies the natural illuminance levels for activation/deactivation road lighting at different road grades: 30 lx for expressways and arterial roads, and 20 lx for secondary roads and branch roads [14]. In the research report of the International Commission on Illumination (CIE), the natural illuminance thresholds for activation/deactivation of road lighting vary from 7.5 to 50 lx depending on road grades [15]. The activation/deactivation of road lighting is based on the standard illuminance values for road lighting at night. However, directly using these standard illuminance values as the threshold for activation/deactivation strategies overlooks the impact of dynamic changes in background natural light illuminance on drivers' visual recognition abilities and many pose potential hazards to traffic safety [16]. During dawn and dusk periods, when the road lighting environment undergoes a day-night transition, the characteristics of natural light change in complex ways depending on the movement of the sun. In addition to variations in illuminance values, which represent light intensity, that impact drivers' visual recognition ability, CCT and CRI, parameters characterizing the

color state of natural light, also change significantly [17]. These alterations modify the color contrast between road obstacles and their background, thus affecting drivers' ability to recognize road obstacles [18]. Therefore, road lighting control strategies should consider not only the changes in natural lighting illuminance but also the relationship between the dynamic variations in natural light CCT and CRI during dawn and dusk, and their impact on drivers' safe visual recognition capability.

In the research on nighttime road lighting control strategies, existing studies and standards have conducted research and made provisions from the perspectives of road grade, traffic volume, and time [14]. However, there is less consideration for the impact of light source characteristics, such as color temperature and color rendering index of nighttime road lighting, on drivers' visual recognition ability. Fotios et al. studied the effect of light source CCT on perceived brightness using a brightness matching method [19,20]. Their research demonstrated that, under the same illuminance, high-color-temperature light sources yield significantly higher perceived brightness than low-color-temperature ones. Kim et al. obtained better lighting effects from illumination sources with varying CCT and CRI by adjusting these parameters [21]. Regarding color perception, Jiang et al. examined the influence of light source spectra on color vision under mesopic conditions, confirming that CCT differences affect the perception of color saturation [22].

In research on the evaluation methods of drivers' visual recognition ability under the influence of road lighting environment, researchers have adopted evaluation indicators such as probability of target object recognition [23], reaction time [24], and visual recognition distance [25]. Given that the primary visual task of drivers during driving is to timely detect road obstacles at a sufficient distance, using drivers' visual recognition distance of obstacles as an evaluation indicator for driving safety and analyzing the threshold requirements for road lighting light environment quality based on this can enable the formulation of more direct and effective road lighting control strategies [26].

In summary, the current judgment criteria for distinguishing daytime and nighttime in the road lighting environment, as well as the control strategies and threshold standards for nighttime road lighting facilities, are not yet perfect. During the operation of road lighting control systems, this imperfection is prone to causing traffic safety risks or energy waste. To obtain reasonable threshold values for road lighting activation/deactivation control judgment indicators and nighttime lighting indicators, this study aims to conduct real-vehicle visual recognition tests for small targets based on an analysis of drivers' visual recognition needs and the mechanism of how natural light and artificial lighting characteristics affect drivers' visual recognition ability. The study aims to investigate reasonable threshold values for road lighting activation/deactivation indicators and nighttime road lighting indicators, and optimize road lighting control strategies accordingly. The findings will provide a reasonable basis for improving the effectiveness of road lighting control strategies.

2. Analysis of the Impact of Natural Light Characteristics on Drivers' Visual Recognition Capability

The quality of the lighting environment on roads is a crucial foundation for ensuring driving safety. However, constrained by the periodic changes in natural illumination, the lighting environment on roads exhibits significantly different characteristics during the day and night. During fine weather in the daytime, sufficient solar radiation forms a high-intensity, full-spectrum natural lighting system, creating a sharp contrast between road obstacles and the background [27]. At this time, the driver's visual system operates under a photopic vision mechanism dominated by cone cells, enabling precise capture of the spatial details and chromaticity of obstacles. This provides drivers with clear and reliable visual perception information, ensuring robust recognition ability for obstacles ahead on

the road [28]. During nighttime, natural light is entirely absent, and road lighting relies exclusively on artificial facilities. The illuminance at night is generally low, placing the visual system in a mesopic vision state where both cone cells and rod cells work together. The driver's visual function is directly influenced by the illuminance level. When the road illuminance is higher, the driver's ability to distinguish spatial details and colors of obstacles is enhanced, and their recognition ability consequently improves [29]. Due to the periodic changes in natural light, the dawn hours (from daybreak to sunrise) and the dusk hours (from sunset to nightfall) are distinct from the strong light conditions of the daytime and fundamentally different from artificial lighting at night. The dynamic changes during these periods pose unique challenges to drivers' visual adaptation and driving safety, serving as crucial transitional stages in the day-night alternation of road lighting environments, as illustrated in Figure 1. Identifying the "critical points" of day-night transition during dawn and dusk that affect drivers' safe visual recognition needs is significant for achieving appropriate switching strategies for road lighting activation/deactivation to ensure a safe and comfortable lighting environment for driving.

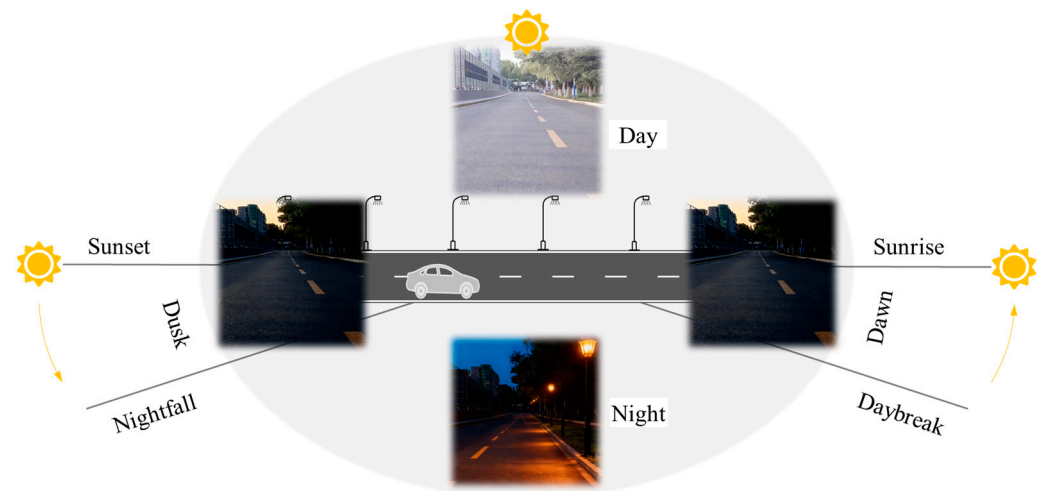


Figure 1. Periodic changes in road lighting environment.

To clarify the impact of different types of lighting sources, such as natural lighting and artificial lighting, on drivers' visual recognition ability during the diurnal transition of road lighting environments. Firstly, taking Beijing as an example, natural light data were collected during the dawn hours (from daybreak to sunrise) and the dusk hours (from sunset to nightfall). The three key indicators of natural light, illuminance, CCT, and CRI, were selected to comprehensively describe the characteristics of the lighting source and their combined effects on drivers' visual perception and obstacle visibility [30]. To ensure that the natural light data were not affected by environmental factors, the data collection sites were chosen in open areas where natural light directly shines without being obstructed by any objects. Furthermore, to avoid the influence of variations in natural light scattering and refraction resulting from differences in cloud thickness on the patterns of natural light changes, data were collected under both clear and cloudy weather conditions, and graphs depicting the variation patterns of natural light illuminance, CCT, and CRI, as shown in Figure 2, were plotted.

In terms of the impact of illumination on drivers' visual recognition ability. The natural light illuminance values during the dawn and dusk transition periods are shown in Figure 2a. The illuminance of natural light during dawn gradually increases over time, while that during dusk gradually decreases. Under both clear and cloudy conditions, the illuminance values of natural light exhibit the same variation pattern, ranging from 0 to

3000 lx. The illuminance value of road lighting at night ranges from 8 to 30 lx. As the illuminance of the road lighting environment changes, the perceived brightness difference (ΔL) between the brightness of road obstacles (L_0) and the brightness of the road (L_b) for drivers will vary proportionally (k) with the light brightness level, as indicated in Equation (1) [31]. When the illumination value decreases, the perceived brightness difference between obstacles and the road correspondingly diminishes, resulting in a reduced visual recognition distance for drivers. Conversely, as the perceived brightness difference increases, the visual recognition distance also increases.

$$\Delta L' = kL_0 - kL_b = k\Delta L \quad (1)$$

where, ΔL is the perceived brightness difference between the obstacles and road, (cd/m^2); L_0 is the perceived brightness of the obstacles, (cd/m^2); L_b is the perceived brightness of the road (cd/m^2), and k is the proportional increase coefficient of lighting perceived brightness.

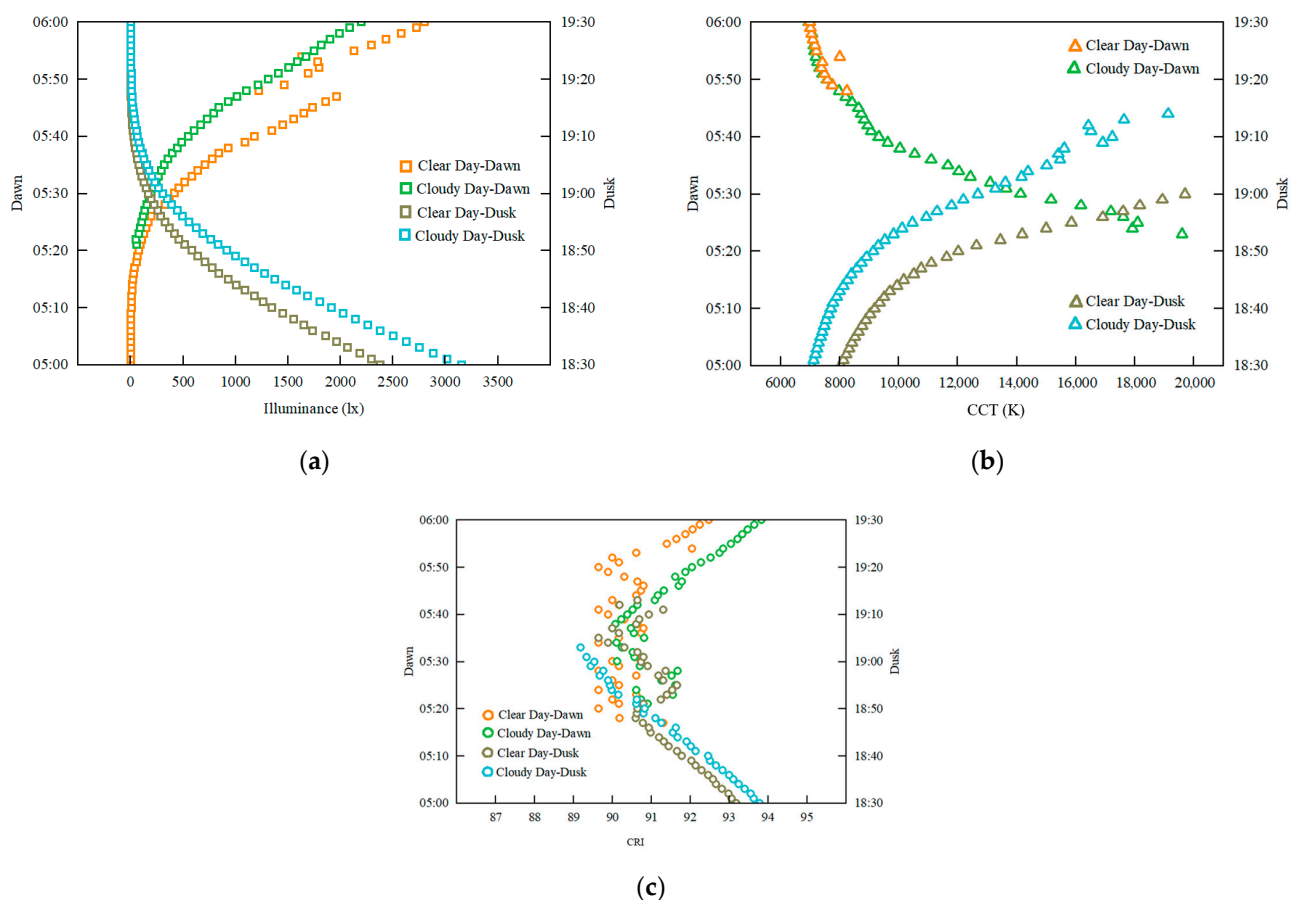


Figure 2. Variation patterns of natural light characteristics: (a) Illuminance values; (b) Correlated color temperature values; (c) Color rendering index.

In terms of the impact of CCT on road lighting on drivers' visual recognition ability. The CCT of road lighting is an indicator that describes the color state of light emitted by a light source. Light from low-color-temperature sources appears warm and yellowish, while light from high-color-temperature sources appears cool and bluish. The CCT of different lighting sources is determined by their spectral distribution characteristics. Low-color-temperature sources contain more long-wavelength light, with a higher proportion of red light in the spectrum, whereas high-color-temperature sources contain more short-wavelength light, with a higher proportion of blue light in the spectrum. The natural light CCT values during the dawn and dusk periods are shown in Figure 2b. The CCT of

natural light during dawn gradually decreases over time, while that during dusk gradually increases. The range of CCT values for natural light during these periods is 7000 to 20,000 K, significantly higher than the 5000 to 6000 K range of natural light during the daytime and the commonly used 3000 to 6000 K range for artificial lighting at night [32]. The color temperature range of the lighting source for nighttime illumination is between 3000 and 6500 K.

The illuminance values of natural light during the dawn and dusk periods cover both mesopic and photopic vision illuminance ranges, and the illuminance of artificial lighting at night falls within the mesopic vision range. The impact of CCT values on drivers' visual recognition ability varies under different lighting illuminance levels. Under photopic vision conditions, in an illumination environment with an excessively high CCT (i.e., containing more blue light components), the cone cells in the human eye are more highly activated, leading to clearer presentation of object edge details on the driver's retina and enhancing the eye's ability to perceive high-contrast details [28].

Under mesopic vision conditions, illumination light of different colors affects drivers' perception of the brightness and color of objects within their field of vision. The spectral power distribution (SPD) of the lighting source and the spectral luminous efficiency function (Figure 3) serve as the foundation for calculating human eye's perceived brightness [1]. The mesopic model MOVE (Mesopic Optimization of Visibility and Efficiency) employs a linear combination of the photopic and scotopic spectral luminous efficiency functions as the human eye's spectral luminous efficiency function, as shown in Equation (2).

$$M(x)V_{MOVE}(\lambda) = xV(\lambda) + (1-x)V'(\lambda) \quad (2)$$

where, $M(x)$ is the normalization factor; $V_{MOVE}(\lambda)$ is the relative spectral luminous efficiency function under mesopic vision; $V(\lambda)$ is the photopic spectral luminous efficiency function; $V'(\lambda)$ is the scotopic spectral luminous efficiency function; and x is the weighting factor, with a range of [0, 1], where $x = 1$ under photopic conditions and $x = 0$ under scotopic conditions.

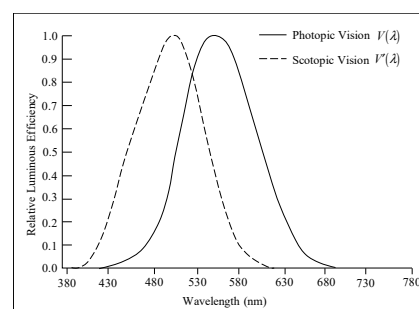


Figure 3. The spectral luminous efficiency function.

In the MOVE model, x represents the proportion of the photopic spectral luminous efficiency function within the mesopic spectral luminous efficiency function. This proportion is influenced by the ratio of the luminous flux of the lighting source under photopic and scotopic conditions, with the degree of influence quantified by the S/P ratio, as shown in Equation (3). The relationship between the CCT of different lighting sources and the S/P values is calculated and illustrated in Figure 4. Yang et al.'s research reached the same conclusion [29]. As the S/P value of a lighting source increases, the human eye's perceived brightness also increases.

$$S/P = \frac{\phi_S}{\phi_P} = \frac{1700 \int_{380}^{780} P(\lambda)V'(\lambda)d\lambda}{683 \int_{380}^{780} P(\lambda)V(\lambda)d\lambda} \quad (3)$$

where, ϕ_S is scotopic luminous flux; ϕ_P is photopic luminous flux; $P(\lambda)$ is the SPD of lighting sources.

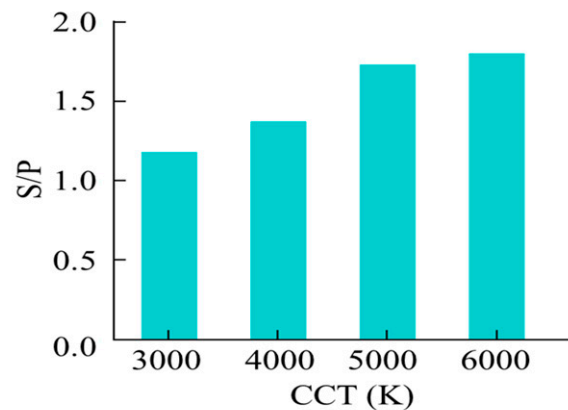


Figure 4. S/P ratio of light sources with different CCT.

When the CCT of road lighting sources increases, the short-wavelength components in the SPD of the light source increase. As calculated by Equation (3), this leads to a higher scotopic luminous flux and a lower photopic luminous flux. The S/P ratio of the lighting source increases, and drivers perceive the brightness of the road lighting environment as proportionally brighter [29]. A reasonably high CCT environment contributes to improving drivers' visual recognition ability. However, the blue light component in an excessively high CCT illumination environment can excessively activate the rod cells (responsible for black-and-white vision discrimination) while suppressing the signals from cone cells responsible for color vision discrimination, thereby reducing the eye's contrast sensitivity and affecting drivers' visual recognition ability [33]. As shown in Figure 5, which illustrates the visual performance level of the human eye under mesopic vision conditions, as the CCT increases, the reaction time of visual performance initially decreases and then increases [34]. Therefore, the changes in natural light CCT during the dawn and dusk periods can affect drivers' visual perception ability and driving safety.

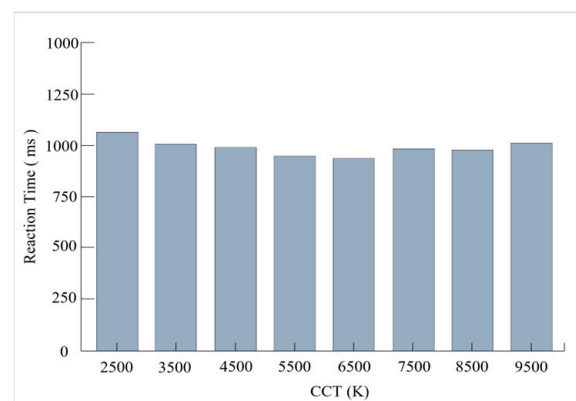


Figure 5. Relationship between CCT and visual performance reaction time.

In the impact of road lighting CCT on perceived color, the obstacles and road form a unique SPD by reflecting the light emitted from the lighting source. By integrating the reflected SPD of the obstacle and road separately with the color-matching functions, the tristimulus values X , Y , and Z for the obstacle and road can be obtained, respectively, as shown in Equations (4)–(6).

$$X = t \int_{380}^{780} Q(\lambda) \cdot \bar{x}(\lambda) d\lambda \quad (4)$$

$$Y = t \int_{380}^{780} Q(\lambda) \cdot \bar{y}(\lambda) d\lambda \quad (5)$$

$$Z = t \int_{380}^{780} Q(\lambda) \cdot \bar{z}(\lambda) d\lambda \quad (6)$$

where, $Q(\lambda)$ is the SPD of obstacles or road; $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the spectral tristimulus values corresponding to the color-matching functions; t is the factor.

The XYZ values can be converted to the L^* , a^* , b^* values in the CIELAB color space through a nonlinear transformation, as shown in Equations (7)–(9).

$$L^* = 116 \cdot f(Y/Y_n) - 16 \quad (7)$$

$$a^* = 500 \cdot [f(X/X_n) - f(Y/Y_n)] \quad (8)$$

$$b^* = 200 \cdot [f(Y/Y_n) - f(Z/Z_n)] \quad (9)$$

where, $f(q) = q^{1/3}$, $q > 0.008856$; $f(q) = 7.787q + 0.1379$, $q \leq 0.008856$; $q = X/X_n$ or Y/Y_n or Z/Z_n .

The calculation method for color difference ΔE_{ab}^* between obstacles and the road in the CIELAB color space is as shown in Equation (10).

$$\Delta E_{ab}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (10)$$

where, ΔL^* , Δa^* and Δb^* represent the differences between the obstacle and the road for the L^* , a^* and b^* values, respectively.

With the variation of road lighting CCT and its SPD, the reflected SPD of obstacles and road changes accordingly. As calculated by Equations (4)–(10), the color differences between obstacles and the road in the CIELAB color space are shown in Figure 6. As the road lighting CCT increases, the color difference between obstacles and the road gradually decreases.

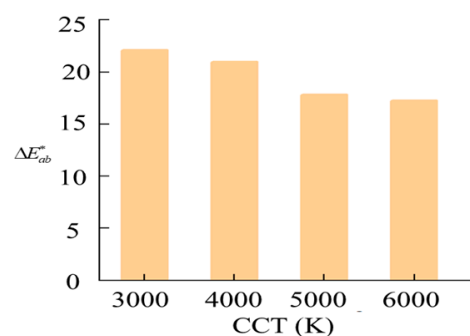


Figure 6. The color difference under different CCTs of the lighting source.

In terms of the impact of the color rendering index of road lighting on drivers' visual recognition ability, the CRI characterizes the ability of a lighting source to reproduce colors and has a direct mathematical relationship with the color difference values that affect drivers' visual recognition ability, as shown in Equation (11) [35]. When the color difference value ΔE changes by 1 unit, the color rendering index Ri changes by 4.6 units. Current research indicates that when $\Delta E \geq 2$, the human eye can perceive color differences, whereas when $\Delta E < 2$, color differences are not easily discernible [36]. The natural light CRI values during the dawn and dusk periods are shown in Figure 2c. The CRI of natural light gradually increases over time in the dawn and gradually decreases during dusk. The CRI values of natural light during these periods range from 87 to 94, indicating relatively high and consistent values. Due to the relatively small variation in the CRI during the dawn and dusk periods (with a difference of 7), the resulting perceived color difference $\Delta E < 2$, which

suggests the change does not significantly impair the human eye's visual perception ability. The CRI of LED light sources used for artificial road lighting at night is about 75, which is a fairly standard and sufficient CRI for road lighting.

$$R_i = 100 - 4.6\Delta E \quad (11)$$

where, R_i is the color rendering index; ΔE is the color difference value.

Based on the above analysis, the illuminance and CCT values of natural light during dawn and dusk, as well as artificial lighting at night, affect drivers' visual recognition ability. The illuminance and CCT of road lighting jointly create the quality of the road light environment, which in turn affects the visibility and visual range of road obstacles [30]. Since drivers must identify obstacles ahead at a sufficiently long distance while driving to allow for the required stopping sight distance to complete the safe driving task of "perception-decision-action" [37]. When, under a certain road lighting environment, the visual recognition distance of drivers to road obstacles ahead exceeds the driving distance required for safe operation, it indicates that the current road lighting environment meets drivers' safe driving needs, as shown in Figure 7. Therefore, as the illuminance and CCT values of natural light change during the dawn and dusk periods, road artificial lighting facilities need to be activated when the visual recognition distance fails to meet the requirements for safe driving; conversely, they should be promptly deactivated. Under artificial lighting conditions at night, at the same illumination, as the CCT of road lighting increases, the perceived brightness difference between obstacles and the road background also increases, which helps enhance the driver's recognition distance. When it is necessary to maintain a certain perceived brightness difference and a safe recognition distance for the driver to ensure driving safety, the illuminance can be appropriately reduced.

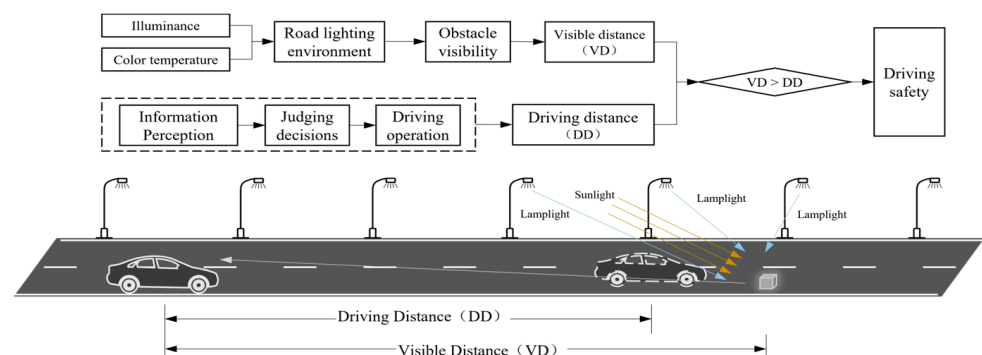


Figure 7. The relationship between road lighting environment and driving safety.

3. Methods

To investigate the dynamic relationship between drivers' visual recognition distance of road obstacles and illuminance and CCT, and based on the visual recognition distance requirements for safe driving, the natural light thresholds for road lighting activation/deactivation were determined, as well as the illumination threshold under different CCT conditions for nighttime road lighting. A real-vehicle visual recognition experiment was designed and conducted.

3.1. Experimental Scheme

Since the visual recognition distance of drivers tends to stabilize due to physiological limitations after the illuminance value of the lighting environment exceeds a certain threshold range [38], the marginal improvement benefit of illuminance changes on visual recognition distance is negligible. To effectively study the impact of natural light variations

on drivers' visual recognition distance, experiments should be conducted during periods with relatively low natural light intensity. Based on the aforementioned analysis of natural light variation patterns in the Beijing area, the time window from sunset to nightfall each day was selected for the experiments. Real-vehicle visual recognition tests were conducted at 5-min intervals, with simultaneous collection of natural light illuminance data. Six tests were completed each day (at 18:50, 18:55, 19:00, 19:05, 19:10, and 19:15), and the experiments were carried out continuously for two weeks to obtain a sufficient number of samples.

To achieve the experimental objectives, in accordance with the relevant specifications [14,39], four CCT levels were chosen: 3000 K, 4000 K, 5000 K, and 6000 K, five illuminance levels were chosen: 7.5 lx, 22.5 lx, 37.5 lx, 52.5 lx, and 67.5 lx. The combination of illuminance and CCT resulted in 20 experimental lighting conditions for testing.

3.2. Experimental Site

The experimental site was selected on an internal road within a school, with a maximum speed limit of 20 km/h. The test road is straight, without significant longitudinal slopes, and its alignment conditions do not affect sight distance. It has a total length of approximately 300 m and features an asphalt concrete pavement. Small targets for visual recognition were placed 30 m away from the end of the test road, ensuring that they only contrasted with the road background in the driver's field of view. The test road runs in a north-south direction, thereby mitigating potential glare from sunlight affecting the drivers. The lighting fixtures are CCT adjustable ones, with a color temperature range of 3000–6500 K and a color rendering index of 75. They are arranged symmetrically on both sides. The experimental site is depicted in Figure 8. During the test, keep the vehicle's headlights on and allow vehicles in adjacent lanes to pass normally.

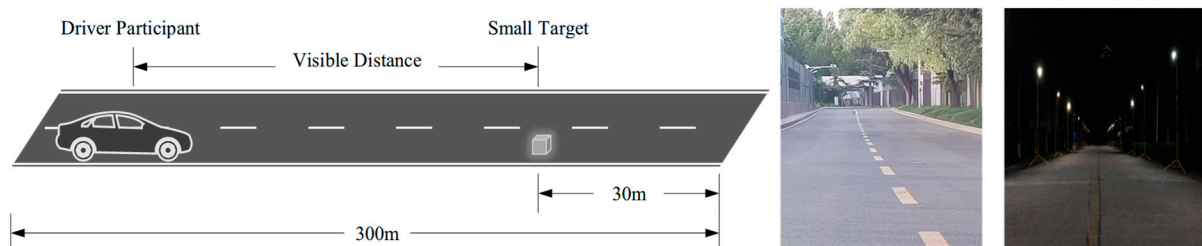


Figure 8. Schematic diagram of test scenario.

3.3. Driver Subjective Evaluation Rating Scale

Based on the visual task of whether drivers can timely identify road surface targets during driving, the detection level for small targets is classified into three grades: clear, general clear, and blurred. The corresponding descriptions are given in Table 1. When the detection level of small targets in the driver's visual field reaches Level 2, it is regarded as the critical state satisfying safe visual recognition [40].

Table 1. Rating scale for small target detection descriptions.

Level	Visibility	Statement	Qualified
1	Clear	Clear outline and accurate identification	Yes
2	General clear	General clear outline	Yes
3	Blurred	Blurred and unclear outline	No

3.4. Small Target

Following the recommendations in CIE 2004, Guide for the Lighting of Road Tunnels and Underpasses [41], a 20 cm × 20 cm × 20 cm grey cube with a 20% surface reflectivity was used as the small target, as shown in Figure 9.



Figure 9. Small target used in the tests.

3.5. Participants

To eliminate the influences of individual differences in age, gender, and cognitive level on the test results and ensure data reliability, recruited participant drivers must meet the specified requirements. According to the data released by the Ministry of Public Security of the People's Republic of China, as of the end of 2024, drivers aged between 26 and 50 account for more than 70% of the total number of drivers. Therefore, to ensure that the participant drivers represent the vast majority of drivers, all participant drivers recruited in the preparation phase of the experiments were aged between 26 and 50. In accordance with the guidelines for human factors experimental design and sample size selection [42,43], the sample size of participant drivers was set at 24. The basic information of the participants is listed in Table 2. Each participant holds a valid C1 license with at least two years of driving experience. Meanwhile, all of them had uncorrected or corrected visual acuity ≥ 4.9 , and had abstained from alcohol and medication for the past week (were well-rested, and exhibited normal reaction times).

Table 2. Details of the participant drivers in the tests.

Number of Participants	License Type	Age (26–45 Years)		Driving Experience (≥ 2 Years)	
		Mean	SD	Mean	SD
Male ($n = 14$)	C1	44.56	10.65	13.25	5.24
Female ($n = 10$)	C1	35.57	7.15	7.57	5.35

Notes: “ n ” represents the sample size, “SD” means the standard deviation, and “C1” refers to a type of driver's license in China that authorizes the holder to drive passenger vehicles with up to 9 seats and a maximum total weight of 4500 kg.

3.6. Instruments and Equipment

A spectroradiometer CL-500A (Konica Minolta, Japan) was used to measure parameters, such as illuminance and color temperature, shown in Figure 10a. The measurement range for illuminance is 0.1~100,000 lx, the color temperature range is 0.1~20,000 K, and the measurement accuracy is better than $\pm 2\%$.

A non-contact, multifunctional speedometer CTM-8C (ZiBo SAGE, China) was used to collect the speed and distance of the vehicles, shown in Figure 10b. The device has a sampling frequency of 60 Hz; a speed range from 0 to 250.00 km/h with a resolution of 0.01 km/h; and a distance range from 0 to 9999.99 m with a resolution of 1 mm.



Figure 10. Test instruments and equipment. (a) Spectroradiometer, (b) Non-contact multifunctional speedometer.

3.7. Experimental Procedure

To collect the visual recognition distance of small targets that meet drivers' subjective recognition needs under different experimental conditions, the specific experimental procedure is shown in Figure 11. Before the experiment begins, participants are instructed on the subjective recognition scale, shown in Table 1. At dusk, the test staff measure the horizontal illuminance and color temperature values of natural light at the location of the small target, or at night, the test staff adjust the CCT of the light source and the illumination. After receiving the start signal, the participant driver departs from the upstream road, accelerates to 20 km/h, and maintains this speed while continuing to drive forward. When the driver spots the small target, judges its visibility to have reached level 2 on the subjective recognition scale, and immediately informs the test staff while maintaining speed. After that, the staff marks point T_1 with the non-contact speedometer. When the test vehicle passes the small target, the staff marks point T_2 with the non-contact speedometer and record the distance between the two marks. This procedure is repeated until the recognition test under all conditions is completed.

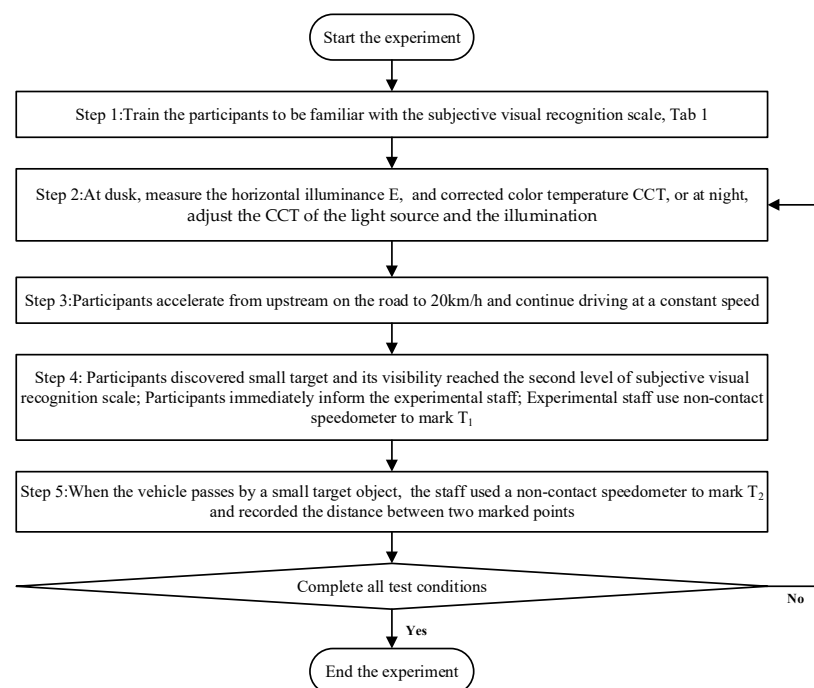


Figure 11. Schematic diagram of the experimental procedure.

4. Results

4.1. Analysis of Driver's Visual Recognition Ability in Natural Lighting Environment

4.1.1. Experimental Data Processing and Analysis

A total of 144 sets of data were collected during the experiment. After removing 16 abnormal data sets caused by pedestrians passing by and obstructing the view during the testing process, 128 sets of valid data were obtained. Statistical analysis of the natural light data collected during the experiment was conducted using SPSS 26.0 software, as shown in Table 3. During the experimental period, the mean natural light illuminance exhibited a significant decreasing trend, with values gradually declining from 514.18 lx to 8.9 lx. Conversely, the mean natural light CCT showed a notable increasing trend, with values gradually rising from 11,302.39 K to 19,741.67 K. Through one-way ANOVA, significant differences were found in the mean natural light illuminance ($F = 741.95$, $p < 0.001$) and mean CCT ($F = 46.74$, $p < 0.001$) at different measurement times. The continuous gradient changes in natural light illuminance and CCT values over time facilitate the analysis of the relationship between these factors and drivers' visual recognition distance.

Table 3. Statistics of natural light illuminance and CCT data.

Time	Illuminance (lx)				CCT (K)			
	Max	Min	Mean	SD	Max	Min	Mean	SD
18:50	624.47	376.6	514.18	64.35	14,944	8321	11,302.39	1942.26
18:55	373.78	216.45	286.227	44	20,000	9610	14,403.65	3592.79
19:00	196.94	89.38	143.78	28.765	20,000	11,858	16,724.17	3004.99
19:00	93.74	31.63	63.925	16.918	20,000	13,630	18,096.51	1972.16
19:10	54.5	13.22	31.29	11.33	20,000	16,086.22	19,087.39	1296.47
19:10	17.6	2.21	8.9	3.98	20,000	18,563	19,741.67	513.81

To explore the correlation between natural light illuminance, CCT, and drivers' visual recognition distance, relationship graphs depicting drivers' visual recognition distance against natural light illuminance and CCT were plotted based on the processed experimental data, as shown in Figure 12. From Figure 12a, it can be observed that as the natural light illuminance increases, drivers' visual recognition distance for small targets gradually increases, indicating a significant positive correlation between natural light illuminance and drivers' visual recognition distance ($r = 0.75$). However, when the visual recognition distance reaches a certain value, the growth trend of the recognition distance flattens out and no longer significantly improves with increasing illuminance, suggesting that drivers' visual recognition ability reaches its physiological limit. From Figure 12b, it is evident that although there are substantial variations in natural light CCT values at the same time on different dates, drivers' visual recognition distances do not change significantly, indicating an extremely weak correlation between natural light CCT values and drivers' visual recognition distances ($r = -0.12$).

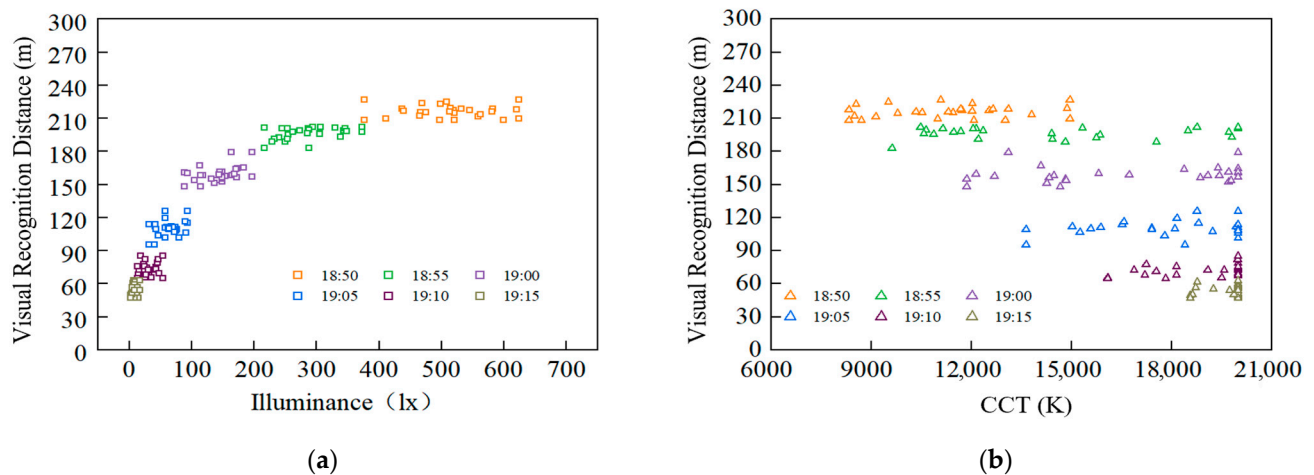


Figure 12. Relationship between natural light characteristics and visual recognition distance: (a) Illuminance; (b) Correlated color temperature.

4.1.2. Driver Recognition Distance Model and Control Strategy Illumination Threshold Optimization

Through the correlation analysis between drivers' visual recognition distance and natural light illuminance and CCT, it is concluded that the natural light characteristic affecting drivers' visual recognition distance is the illuminance value. To further quantify the relationship between drivers' visual recognition distance of small road targets and natural light illuminance, nonlinear fitting analysis was conducted on the experimental data, with natural light illuminance as the independent variable and visual recognition distance as the dependent variable. This resulted in an exponential function regression model describing the relationship between natural light illuminance and visual recognition distance, as shown in Equation (12).

$$D = 219.66 - 175.91 \times 0.99^E \quad (12)$$

where D is the driver's visual recognition distance for small targets (m); E is the natural light illuminance (lx), $E \in (8.91, 514.18)$, with a coefficient of determination (R^2) of 0.97.

Since an increase in driving speed leads to a reduction in drivers' visual cognitive ability and visual recognition distance, the influence of vehicle operating speed must be fully taken into account when determining the lighting control illuminance threshold that ensures driving safety based on the regression model. Based on the speed and visual recognition distance data obtained by Feng [44] in the study, the relationship between drivers' visual recognition distances under dynamic and static conditions was analyzed, as shown in Equation (13).

$$k = 0.39 + \frac{1.06 - 0.39}{1 + e^{\frac{v-76.08}{43.76}}} \quad (13)$$

where k is the reduction factor for the driver's visual recognition distance; v is the speed of the vehicle (km/h), $v \in (0, 100)$, with a coefficient of determination (R^2) of 0.94.

Based on the above analysis, the visual recognition distances of drivers at different speeds were corrected, and the relationship between natural light illuminance and visual recognition distance at different vehicle speeds was obtained, as shown in Equations (14)–(17).

$$40 \text{ km/h} : D = 205.58 - 164.63 \times 0.99^E \quad (14)$$

$$60 \text{ km/h} : D = 188.76 - 151.16 \times 0.99^E \quad (15)$$

$$80 \text{ km/h} : D = 170.46 - 136.51 \times 0.99^E \quad (16)$$

$$100 \text{ km/h} : D = 165.49 - 128.12 \times 0.99^E \quad (17)$$

To ensure driving safety, the visual recognition distance that drivers have for obstacles on the road must be greater than the stopping sight distance required for safe driving. Based on the safe stopping sight distance values corresponding to different operating speeds, as shown in Table 4, substituting different stopping sight distances into Equation (3) for calculation yields the natural light illuminance thresholds corresponding to each stopping sight distance.

Table 4. Threshold values of natural light illuminance at different operating speeds.

Speed (km/h)	Stopping Distance (m)	Illuminance (lx)
40	40	20
60	75	40
80	110	110
100	160	440

4.2. Analysis of Driver's Visual Recognition Ability in Artificial Lighting Environment

4.2.1. The Impact of Artificial Lighting Illuminance and CCT on Visual Recognition Distance

After excluding 35 abnormal data points that were significantly influenced by headlights from vehicles in adjacent lanes, a total of 445 valid visual recognition distance observations were retained for analysis. The experiment adopted a repeated-measures design, in which each participant completed multiple trials under different combinations of road lighting illuminance and CCT. Consequently, observations obtained from the same participant were not statistically independent. To appropriately account for within-participant dependence and inter-individual variability, linear mixed-effects models (LMMs) were employed. In these models, visual recognition distance was treated as the dependent variable, road lighting illuminance and CCT were specified as fixed effects, and participant was included as a random intercept to capture individual differences in baseline visual recognition performance. An interaction term between illuminance and CCT was further tested to examine whether the effect of CCT varied across different illuminance levels.

Prior to model fitting, the normality of visual recognition distance under each experimental condition was examined using the Shapiro–Wilk test. All p -values exceeded 0.05, indicating that the data were approximately normally distributed and suitable for parametric modeling. Model assumptions were further evaluated through residual diagnostics, which revealed no substantial deviations from normality or homoscedasticity. This modeling framework enables valid statistical inference by explicitly accounting for the repeated-measures structure of the experimental data, without requiring independence among observations from the same participant.

The LMM results showed that both road lighting illuminance and CCT had statistically significant effects on drivers' visual recognition distance. Specifically, illuminance exhibited a strong positive main effect ($\beta = 44.41$, $SE = 2.59$, $p < 0.001$, 95% CI [39.32, 49.49]), indicating that higher illuminance levels were associated with longer visual recognition distances. CCT also showed a significant main effect ($\beta = 0.019$, $SE = 0.002$, $p < 0.001$, 95% CI [0.016, 0.022]), suggesting that spectral characteristics of the light source play an important role in visual recognition performance under artificial lighting conditions. In addition, a statistically significant interaction between illuminance and CCT was observed ($\beta = -0.001$, $SE = 0.001$, $p = 0.021$), indicating that the effect of CCT on visual recognition distance varied across different illuminance levels. The variance of the participant-level random intercept was relatively small, suggesting limited inter-individual variability in baseline visual recog-

nitition distance after accounting for the fixed effects. Overall, these results confirm that the observed relationships between illuminance, CCT, and visual recognition distance are robust and not driven by individual differences among participants.

As shown in Figure 13a, when CCT was held constant, increases in road lighting illuminance were associated with longer visual recognition distances for small targets. This effect reflects the enhancement of luminance contrast between the target and the surrounding road surface under higher illuminance conditions, thereby facilitating target detection. However, within the tested illuminance range, the increase in visual recognition distance gradually diminished at higher illuminance levels, suggesting a saturation effect in visual performance. Similarly, under low illuminance conditions, changes in visual recognition distance were relatively limited, which is likely attributable to the increased relative contribution of vehicle headlights to target visibility.

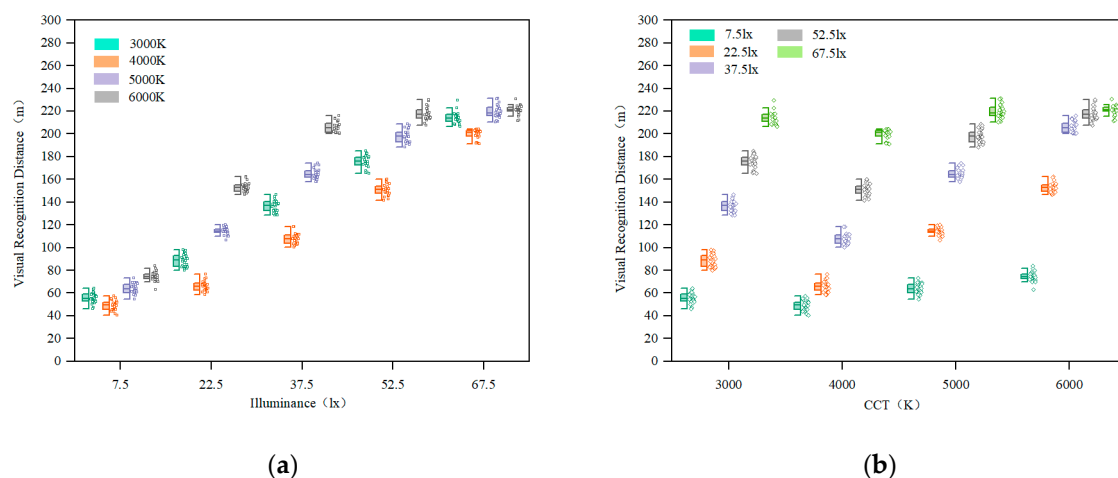


Figure 13. Relationship between road light characteristics and visual recognition distance: (a) Illuminance; (b) Correlated color temperature.

As shown in Figure 13b, under constant illuminance conditions, visual recognition distance exhibited a non-monotonic relationship with CCT: as CCT increased, recognition distance initially decreased and subsequently increased, reaching a minimum at approximately 4000 K and higher values at 6000 K. This pattern indicates that intermediate CCT levels may be less favorable for target recognition compared with higher CCT lighting under artificial illumination. Moreover, the interaction analysis revealed that the effect of CCT on visual recognition distance diminished as road lighting illuminance increased. Specifically, at lower illuminance levels, variations in CCT produced more pronounced changes in visual recognition distance, whereas under higher illuminance conditions, the marginal improvement associated with increasing CCT became progressively smaller. This finding suggests that the influence of spectral characteristics on visual recognition performance is partially constrained when sufficient illuminance is provided.

4.2.2. Establishment of Road Lighting Environment Evaluation Model and Threshold

Based on the preceding analysis, it is evident that a driver's visual recognition distance for road obstacles under varying road lighting conditions is influenced by both illuminance and CCT. When CCT is controlled, a strong positive correlation is observed between road lighting illuminance and visual recognition distance ($r = 0.95$). Likewise, when road lighting illuminance is controlled, a positive correlation is found between CCT and visual recognition distance ($r = 0.69$). To assess whether different combinations of road lighting illuminance and CCT satisfy the driver's safety requirements for visual recognition distance, a fitting model was developed with the driver's visual recognition distance for small objects

as the dependent variable, and road lighting illuminance and CCT as independent variables. The model, as presented in Equation (18), yields a coefficient of determination (R^2) of 0.94, indicating a high degree of fit. For any given combination of road lighting illuminance and CCT, if the driver's visual recognition distance exceeds the required safe stopping sight distance, the lighting conditions are considered to meet the safety standards for driving.

$$D = 144.418 - 0.075 \times T + 4.146 \times E_l + 1.042 \times 10^{-5} \times T^2 - 0.016 \times E_l^2 - 6.667 \times 10^{-5} \times T \times E_l^2 \quad (18)$$

where D is visual recognition distance, m; T is road lighting CCT, K, $T \in (3000, 6000)$; E_l is road lighting illuminance, lx, $E_l \in (7.5, 67.5)$.

Similarly, on the basis of ensuring driving safety, the safe stopping sight distance corresponding to different operating speeds was substituted into the aforementioned fitting model for visual recognition distance. Considering the relationship between static and dynamic visual cognitive abilities and visual recognition distance, the road illumination values that meet the driver's safe visual recognition requirements under different color temperature conditions were calculated, as shown in Table 5.

Table 5. Illumination required for safe driving visibility under different CCT conditions.

Speed (km/h)	Stopping Distance (m)	Illuminance (lx)			
		3000 K	4000 K	5000 K	6000 K
40	40	7.5	7.5	7.5	7.5
60	75	19.5	25.8	22.5	12.3
80	110	29.85	36.45	32.7	19.05
100	160	38.1	58.65	41.4	24.45

4.3. Analysis of Road Lighting Control Strategy

The control process for road lighting activation/deactivation strategies is refined by incorporating vehicle operating speed and natural light threshold values, as illustrated in Figure 14. At dawn, vehicle detection equipment collects the vehicle's operating speed (v), and an illuminance meter measures the road surface illuminance (E_0). As the natural light illuminance gradually increases, road artificial lighting is deactivated at time T_1 when the measured road surface illuminance (E_0) exceeds E_1 ($E_1 = E_2 + E_3$), where E_2 is the illuminance threshold corresponding to the vehicle's operating speed (v) and E_3 is the nighttime road surface illuminance value at a certain CCT. The condition indicates that natural light alone can meet the illuminance requirements of the road lighting environment for safe driving, thereby, preventing energy waste. At dusk, the vehicle detection equipment collects the vehicle's operating speed (v), and the illuminance meter measures the road surface illuminance (E_0). As the illuminance of natural light gradually decreases, the road lighting is activated at time T_2 when the measured road surface illuminance (E_0) falls below the illuminance threshold (E_2) corresponding to the vehicle's operating speed (v), to supplement and improve the quality of the road lighting environment, thereby meeting the visual recognition requirements for safe driving.

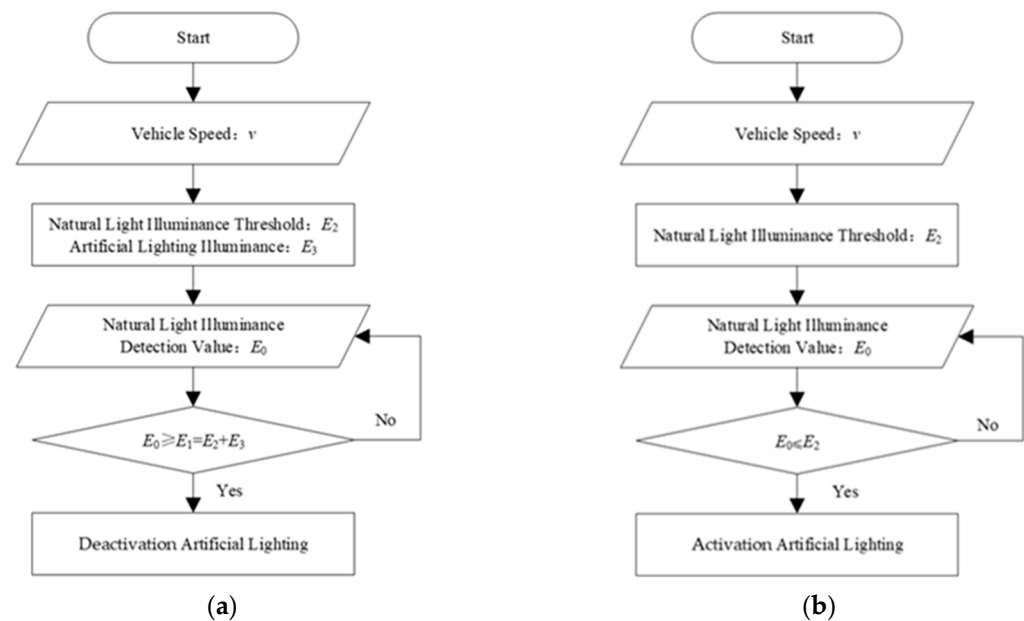


Figure 14. Control strategy for road lighting: (a) Dawn; (b) Dusk.

5. Discussion

This study conducted real-vehicle driving experiments to investigate the visual recognition distance of drivers towards small objects under natural light and artificial lighting conditions. Regression models were established between natural light illuminance and visual recognition distance, as well as between artificial lighting illuminance and CCT and visual recognition distance. Taking into account the visual recognition distance requirements for safe parking by drivers, the natural light illuminance thresholds for activation/deactivation of road lighting facilities under different vehicle operating speeds were calculated, along with the lighting illuminance values under different CCT conditions.

Compared with existing research and standard specifications, when the vehicle operates at a relatively low speed (40 km/h), the natural light illuminance thresholds for road lighting activation/deactivation strategies obtained in this study align with the values specified in the standards. However, when the vehicle operates at higher speeds (60 km/h, 80 km/h, and 100 km/h), the natural light illuminance thresholds for road lighting activation/deactivation strategies obtained in this study are significantly higher than the standard values [12]. This difference is mainly due to the higher background natural light illuminance within the driver's field of view under natural lighting conditions, resulting in a relatively low perceived brightness contrast between obstacles and the road. In contrast, during nighttime illumination by streetlights, the background light illuminance within the driver's visual field is lower, significantly enhancing the perceived brightness contrast between obstacles and the road, making them more easily detectable under the same illuminance level [31].

Compared with the existing standard values, the required illumination values under different color temperature conditions vary for nighttime road lighting. In the mesopic illuminance range, when the LED light source has a higher CCT, the brightness of the road and small targets perceived by the driver increases [45]. This enhances the contrast between small targets and the road background, thereby improving target visibility and increasing the driver's recognition distance. However, as the illuminance of road lighting increases, the perceived brightness differences caused by variations in CCT have a decreasing effect on the driver's visual cells [46], thus reducing the impact of changes in CCT on recognition distance. On the other hand, when using a low-CCT LED light source (3000 K), the driver's

recognition distance is greater than at 4000 K because the color difference between small road targets and the road background is more pronounced at 3000 K [47]. Although the perceived brightness difference between the road surface and small targets is smaller under 3000 K, the greater color contrast between the targets and the road background results in a longer recognition distance compared to 4000 K.

Through the study of the natural illumination threshold when the artificial lighting is activation/deactivation at dusk and dawn under different speed conditions, as well as the illumination threshold of artificial lighting under different CCT and speed conditions at night, the activation/deactivation time of the road artificial lighting control strategy and the illumination value at night are optimized, which is conducive to the accurate regulation of lighting resources and the effective balance of driving safety and energy efficiency while ensuring the demand for safe sight distance.

In terms of the impact of natural light characteristics on drivers' visual recognition distance, an analysis of experimental data reveals that variations in natural light illuminance significantly affect drivers' visual recognition distance. Specifically, as natural light illuminance increases, drivers' visual recognition distance for small objects on the road also increases. This is because the perceived brightness contrast between small objects and the road intensifies, enhancing drivers' ability to recognize these small objects [31], a finding that is largely consistent with existing research conclusions. However, under excessively high CCT conditions, as CCT rises, the human eye's sensitivity to visual perception in the light environment exhibits diminishing marginal effects. Simultaneously, the color contrast variation between road obstacles and the road decreases [18]. Consequently, the limited observed changes in natural light CCT during dusk do not result in significant variations in drivers' visual recognition distance.

This study only investigated the variation pattern of drivers' visual recognition distance for small objects on asphalt pavement in relation to natural light illuminance. When the pavement material varies, it can also influence drivers' recognition distance for small objects on the road [48], which necessitates further supplementation and refinement in subsequent research. On the other hand, the experimental data solely collected recognition data under different weather conditions of clear and cloudy days, without analyzing recognition data under adverse weather conditions, such as rainy and foggy days that affect road visibility [49,50]. Therefore, the natural light illuminance thresholds for activating/deactivating road artificial lighting under corresponding adverse weather conditions should be studied separately.

6. Conclusions

This study investigates the influence of illuminance, CCT, and CRI of lighting sources on the driver's visual recognition ability. Experiments were conducted to evaluate visual recognition distances for small road obstacles under natural light and artificial lighting conditions. The study established natural light illuminance as a criterion for controlling road lighting activation/deactivation, considering both color temperature and illuminance for nighttime lighting. Regression models were developed to calculate the natural light illuminance thresholds for activating/deactivating artificial lighting and the illuminance thresholds for artificial lighting under various CCT conditions.

The results show that at low speeds (40 km/h), the natural light illuminance thresholds for road lighting activation/deactivation align with current standards. However, at higher speeds (60 km/h, 80 km/h, and 100 km/h), these thresholds increase significantly, reaching 2, 5.5, and 22 times the standard values, respectively. This indicates potential safety risks when using current standards at speeds ≥ 60 km/h.

Furthermore, the study found that at night, the required road lighting illuminance varies with vehicle speed and light source CCT. As CCT increases, the driver's visual recognition distance initially decreases and then increases. At 4000 K, the recognition distance is minimal, while at 6000 K, it is maximal. At 60 km/h, 80 km/h, and 100 km/h, the illuminance thresholds decrease by 52.32%, 47.74%, and 58.31%, respectively. This suggests that high CCT conditions allow for a reduction in illuminance, supporting road lighting energy efficiency.

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