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Research Article

Study on Drivers' Visual Load Features in Lighting Environments of Interior Zones of Extra-Long Tunnels over 10 km

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In extra-long road tunnels (>10 km), the interior zone accounts for 95% of the total tunnel length. Driving for an extended period in the interior zone of such a tunnel in a monotonous and dimly lit environment causes heavy visual loads for drivers and undermines the safe operation of tunnels and driving comfort. This study investigated the changing patterns of drivers' visual loads while driving through road tunnels. In a real vehicle experiment, the pupil diameter, fixation duration, electroencephalogram power spectral density, standard deviation of normal to normal, and root mean square of successive differences were used as indicators of drivers' visual loads. By comparing the differences in psychological and physiological parameters in tunnels of four different lengths, this study discovered the changing pattern of drivers' visual loads in the interior zone of extra-long tunnels and merged multi-source information of various indicators based on the entropy evaluation model to obtain comprehensive visual load values for drivers. The experiment revealed that as the tunnel length increased, the changing patterns of the drivers' visual load indicators diverged. In particular, the driver's tension levels began to spike after 180s of driving. The comprehensive visual load values of drivers, combined with the change features of multiple indicators, provide a more accurate and complete assessment of visual loads. The analysis of drivers' visual load features can provide a theoretical basis for measures to optimise the lighting environment of the interior zone of extra-long tunnels over 10 km.

1. Introduction

With the development of road tunnels, the number of tunnels longer than 10 km has increased. Currently, 16 extra-long road tunnels longer than 10 km have been built in China, 21 are under construction, and five are in the planning phase. In the future, the scale of extra-long (over 10 km) road tunnel construction and the number of such tunnels will continue to increase [1]. Compared to regular long tunnels, the interior zone of a 10 km tunnel is longer. For example, the length of the interior zone of the Qinling tunnel is 17,567 m, which is 97.49% of the total tunnel length. This entails driving in a monotonous, closed, and dim environment for an extended period, which poses a significant safety hazard.

Therefore, the lighting environment of extra-long road tunnels of over 10 km has been actively studied. Qin et al. conducted an experiment using real vehicles to study the changes in heart rate variability (HRV) of drivers when they drove through the interior zone of tunnels over 10 km. Their experimental results revealed that drivers are highly nervous when driving in the interior zones of tunnels, and special light zones can help alleviate their anxiety [2]. Zhao et al. studied the characteristics of driving and drivers' vision under the lighting of extra-long road tunnels and found that retroreflective arches can effectively improve driver safety [3]. Yan et al. focused on the influence of special light zones on drivers' eye movement parameters and found that in special light zones, drivers' fixation points are more scattered, thus ensuring a better driving experience [4].

These studies were focused on the measures for improving the lighting environment in extra-long road tunnels over 10 km. However, few studies have been conducted on the response patterns of driver visual loads in extra-long tunnels.

Currently, research on the lighting environment of tunnels typically uses various psychological and physiological parameters to indicate the visual workload of the drivers. Gao et al. used the change rate of drivers' pupil sizes while approaching a tunnel and pointed out that driving safety at the tunnel entrance can be improved through the methods of visual workload evaluation [5]. Du et al. studied the changes in drivers' pupil sizes at the entrance and exit of a tunnel to determine the time of continuous visual vibration and used them as an indicator to measure drivers' visual workloads and evaluate the driving safety levels at the entrance and exit of the tunnel [6]. He et al. described the visual workload difference of drivers in different lighting of tunnel sidewalls with indicators, including the visual fixation area, fixation time, fixation frequency, pupil diameter, and change rate [7]. Using a different indicator, the velocity of instantaneous maximum pupil size for drivers' visual workloads, Jiao et al. found that in underwater urban tunnels, owing to better lighting, the time drivers take to adapt to brightness and darkness is shorter, and the driving experience is more comfortable than that in regular tunnels [8]. Guo et al. studied the influence of different emotion-inducing materials on drivers' visual workload, and heart rate (HR) was used to indicate the drivers' visual workload [9]. Moreover, Zhu et al. adopted HRV as an indicator of drivers' visual workload to study the influence of familiarity with the road environment on drivers' visual loads and found that drivers familiar with the road in the experiment had significantly lower visual loads than those who were not familiar with the road [10]. Finally, Feng et al. used heart rate (HR) to measure drivers' visual loads and discovered that drivers exhibited higher visual loads when driving downhill than when driving uphill [11].

Currently, the commonly used indicators for drivers' visual loads in the lighting environment of tunnels are drivers' eye movement parameters (such as pupil diameter, fixation duration, and fixation area) and electrocardiography (ECG) parameters (including HR and HRV), whereas electroencephalogram (EEG) parameters are less commonly used. Different psychological and physiological parameters reveal different aspects of drivers' visual loads. Specifically, pupil diameter signifies the driver's capability to obtain visual information [12]. When the lighting is dim, pupils dilate to satisfy the requirement to acquire sufficient visual information. Fixation time reflects the visual efficiency of the driver [13]. For example, when they feel uncomfortable with lighting, they require a longer fixation duration to ensure the safe completion of visual tasks. In addition, the EEG parameters show the soberness of the drivers [14], and the ECG parameters indicate their tension levels during driving [15]. Therefore, there are discrepancies among the different indicators of drivers' visual loads. Scholars have suggested combining information from diverse sources to obtain an indicator for measuring drivers' visual loads when driving in tunnels [16].

Therefore, in this study, a real vehicle experiment was conducted in an outdoor environment to study the changing patterns of drivers' psychological and physiological parameters while driving through the interior zone of extra-long tunnels over 10 km. These parameters were compared with the psychological and physiological parameters of drivers driving through tunnels of other lengths. Then, the characteristics of drivers' visual loads in the interior zone of 10 km extra-long channels were analysed. Finally, the entropy evaluation method was used to integrate the multi-source data of the drivers' psychological and physiological parameters and acquire the drivers' comprehensive visual load values.

2. Experiment Design of Interior Zone in Extra-Long Tunnels over 10 km

2.1. Tunnel Selection for Experiment. This experiment needs to determine the characteristics of drivers' visual load under the lighting environment in the interior of 10 km extra-long tunnel by comparing the characteristics of drivers' visual load changes during driving in the interior of tunnels with different lengths. At the same time, in order to ensure that other factors affecting the experimental data (such as traffic flow, natural light, and so on) are as uniform as possible, different tunnels on the same expressway are selected for research.

Four tunnels in the Baotou-Maoming Expressway, the Nanwutai tunnel (2,564 m), Huangtuliang tunnel (230 m), Qingcha tunnel (1,800 m), and Qinling tunnel (18,020 m), were selected for the experiment. The characteristic parameters of the tunnels are illustrated in Table 1. The experiment studied the characteristics of drivers' visual loads when driving in the interior zone of an extra-long tunnel of over 10 km by comparing the differences between drivers' psychological and physiological parameters in the interior zones of tunnels of different lengths. The characteristic parameters for each tunnel are listed in Table 1. The position and lighting environment parameters for each tunnel are shown in Figure 1 and Figure 2, respectively.

2.2. Selection of Indication Factors for Drivers' Visual Loads. Research has revealed that 80% of the information a driver acquires while driving is visual [17]. Such information under the lighting of a tunnel is reflected in the retinas through pupils, sensed by the visual nerves, and transmitted to the visual cortex of the human brain, which then guides various organs of the human body via the nervous and endocrine systems to respond to the environment. As such, most studies on the lighting environment of tunnels have analysed all the types of psychological and physiological indicators of drivers and have provided guidance, based on knowledge about the patterns of drivers' response to the lighting environment, for the design and improvement of the lighting environment.

2.2.1. Eye Movement Parameters. The visual information received by the driver was transmitted through the pupils to the visual cortex. When the visual environment is dimly lit, it

Table 1: Characteristic parameters of the tunnels.

Tunnel name	Total length (m)	Length of interior zone (m)	Light arrangement	Lighting devices
Nanwutai	2564	2267	Symmetrical lighting on both sides	Yellow high-pressure sodium lamp
Huangtuliang	230	134	Lighting on one side	Yellow high-pressure sodium lamp
Qingcha	1800	1503	Symmetrical lighting on both sides	Yellow high-pressure sodium lamp
Qinling	18020	17567	Symmetrical lighting on both sides	Yellow high-pressure sodium lamp

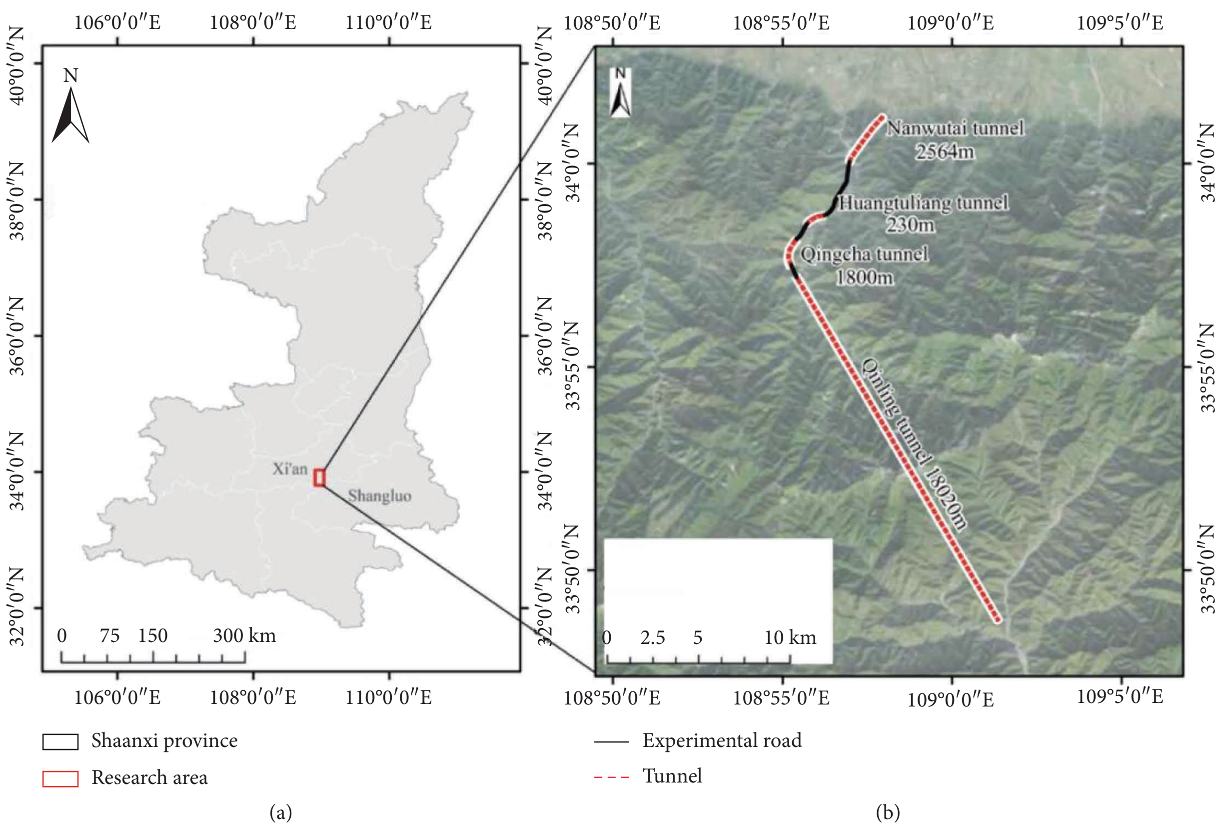

Figure 1: (a) Shaanxi province. (b) Location of the tunnels.

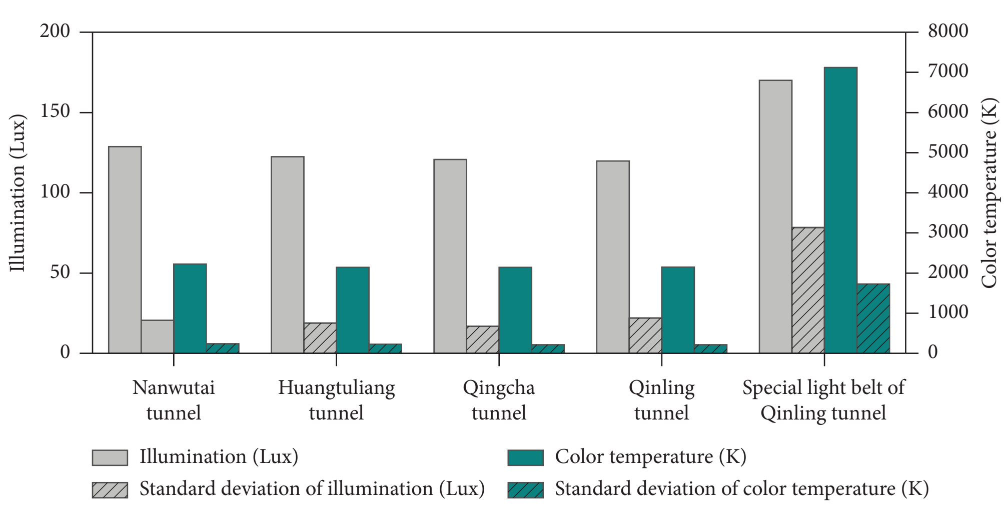

Figure 2: Lighting environment of the interior zones of each tunnel in the experiment.

becomes difficult for the driver to obtain visual information, and the human body then dilates the pupil through neural regulation to ensure that good-quality visual information is acquired. Thus, the pupil diameter can effectively indicate the difficulty with which drivers obtain visual information [12].

Fixation duration is an important indicator of drivers' visual load. Ai utilised the HMM model to study the influence of the geometric features of crossroads on drivers' visual loads and found that the efficiency of drivers' cognition, judgment, and decision making is strongly correlated with the duration of visual fixation [18]. The shorter the duration, the stronger the visual efficiency of the driver. Similarly, a longer duration indicated weaker visual efficiency. Therefore, fixation duration is highly suitable for analysing drivers' visual loads from the perspective of visual efficiency. In this experiment, the fixation durations of the drivers were categorised into three groups. The first group consisted of short durations ranging from 0 to 200 ms. The second group consisted of medium durations, covering a range of 200 to 400 ms. The last group comprised long durations, including 400 to 1000 ms durations. Subsequently, the distributions of these three groups in different lighting environments of the tunnels were analysed.

2.2.2. EEG Parameters. Scholars have conducted numerous studies on EEG monitoring of visual loads. Wang et al. conducted an experiment on simulated driving on monotonous roads and determined four indicators to describe the physiological state of drivers: $(\theta+\alpha)/\beta$, β/α, $(\theta+\alpha)/(\alpha+\beta)$, and θ/β, where θ denotes the break of consciousness and relaxed state of the body; α denotes the sober and relaxed state of the brain, which is not easily perturbed by the environment; and β stands for a state of strong emotion, nervousness, vigilance, and deep concentration. Their ratios signify an antagonistic effect between the relaxation and excitement. As the visual load increased, these ratios increased, and the $(\theta+\alpha)/\beta$ ratio exhibited the largest increase [19, 20]. Therefore, this experiment selected $(\theta+\alpha)/\beta$ as the indicator for measuring the level of driver soberness while driving.

2.2.3. ECG Parameters. Heart rate variability (HRV) refers to the minor fluctuation between two normal heart rates (*R*-*R*) subject to high-level neural activity, the spontaneous rhythmic activity of the central nervous system, breathing, and cardiovascular responses transmitted through pressure and chemical sensors. These factors influence the comprehensive modulation effect of the sympathetic and parasympathetic nerves and eventually affect the fluctuation of heart rates. Therefore, HRV reflects the intensity and balance of cardio-sympathetic and parasympathetic neural activities [21]. Eilebrecht and Wolter suggested in their research that HRV accurately reflects the tension levels of drivers while driving [22].

The experiment adopted a time-dimension analysis of the changes in drivers' standard deviation of normal to normal (SDNN) and root mean square of successive differences (RMSSD). The equations used are as follows.

SDNN (ms) is the indicator of the deviation between a driver's heart rate and a normal heart rate, which is calculated as the variance of all periods between two consecutive heart rates (*R* and *R*) during driving, as follows:

$$\text{SDNN} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(RR_i - \overline{RR}\right)^2}. \tag{1}$$

RMSSD (ms) is the indicator of the rapid changes in a normal heartbeat period, which is calculated as the average square root of two consecutive heart rates during driving, as follows:

$$\text{RMSSD} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}\left(RR_{i+1} - RR_i\right)^2}. \tag{2}$$

The RMSSD is the average value of the period between two consecutive heart rates. RR_{i+1} denotes the value of the period between $i+1$ consecutive heart rates.

2.3. Experiment Process. At present, there is no consensus on the number of subjects using visual and ECG features in the field of tunnel lighting research, which is generally 4 to 8. In order to ensure sufficient accuracy of these parameters, a certain amount of measured samples must be guaranteed. With the measured speed as the required accuracy parameter [8], the minimum measured sample size under ideal conditions is calculated as follows:

$$N = \left(\frac{\sigma K}{E}\right)^2, \tag{3}$$

where N is the required sample size; σ is the overall standard deviation, assuming that the standard deviation of speed is 5~10 km/h; and K is a constant, a statistic under the confidence level. When the confidence level is equal to 95%, $K = 1.96$; E is the allowable error, assuming that the allowable speed error is 5 km/h. Then, $4 \le N \le 16$.

The study subjects were 10 healthy male volunteers with an average age of 42.3 years. To maintain the same lighting environment for all drivers and to eliminate its impact on the experimental results, the duration of the experiment was set from 10:30 to 14:30. The drivers wore the SensoMotoric Instruments (SMI) eye tracker and Biopac MP150 physiological recorder, which recorded variations in their pupil diameters and EEG and ECG parameters, respectively. The volunteers are required to maintain a speed of 80 km/h as much as possible during driving. The detailed volunteer information, experimental instruments, and flow are illustrated in Table 2 and Figures 3 and 4, respectively.

3. Experiment Results and Analysis

3.1. Comparison of Drivers' Pupil Diameter in Different Tunnels. By comparing the pupil diameter changes of the drivers in each tunnel, as shown in Figure 5, it was found

Table 2: Volunteer information.

Age	Actual driving years	Physical condition	Number of experiments
42.3 ± 8.4	18.4 ± 3.4	Normal visual skills, no physiological defects and major accident experience	Two experiments per person

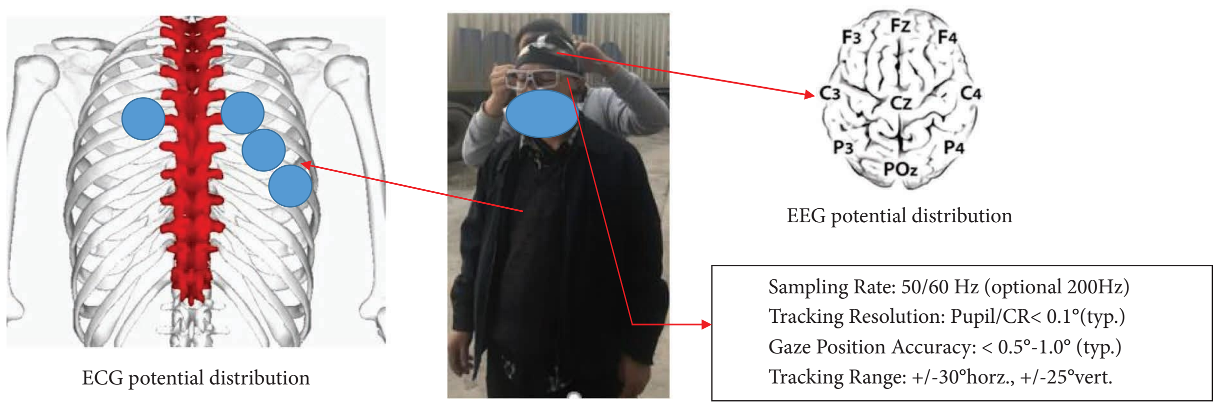

Figure 3: Subject wearing equipment.

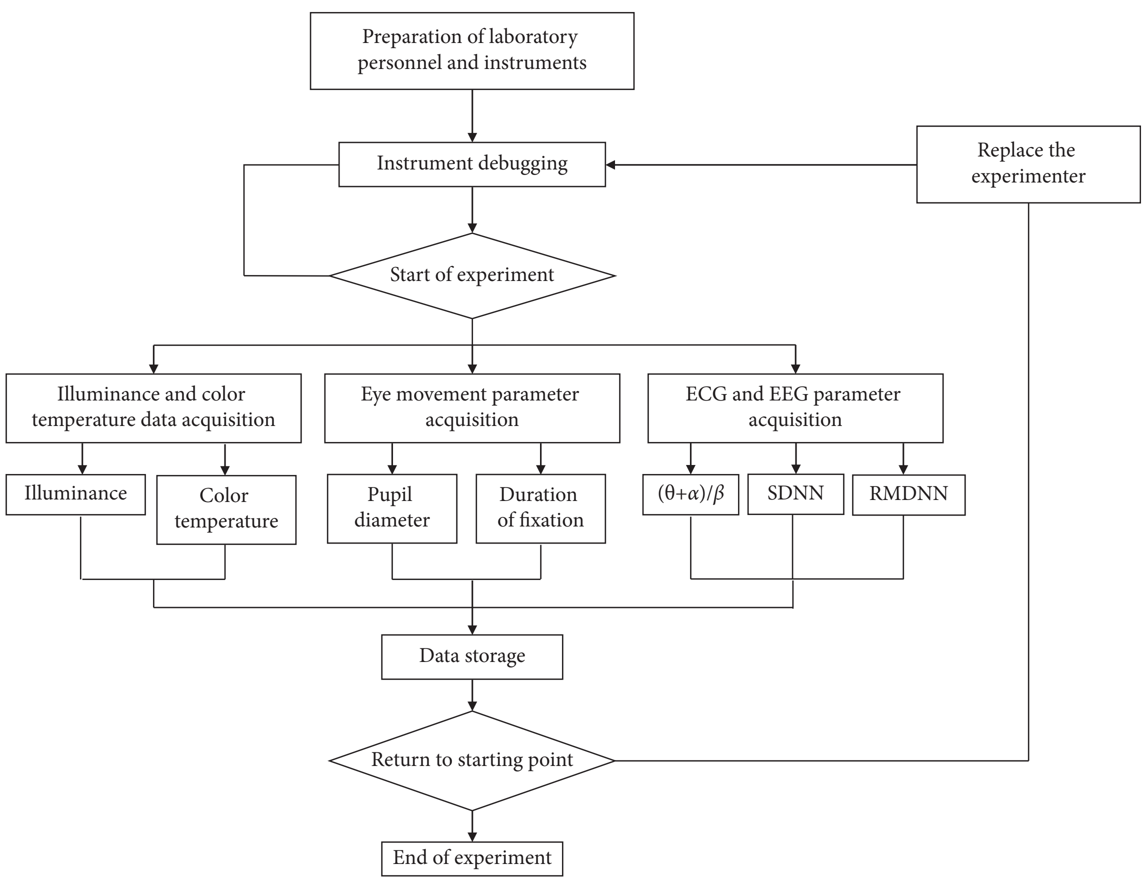

Figure 4: Flowchart of the experimental process.

that the diameter changes were more stable when the drivers were driving in the interior zone of the tunnels. However, the diameters differed significantly according to the length of the tunnels. Specifically, the maximum pupil diameter of the drivers in the Qinling tunnel was 5.83 mm, which is 38.15%, 11.05%, and 14.09% longer than those of the drivers in the Huangtuliang, Nanwutai, and Qingcha tunnels, respectively. Figure 6 shows the average pupil diameter of the drivers in the interior zone of the tunnels. The average pupil diameter of drivers in the Qinling

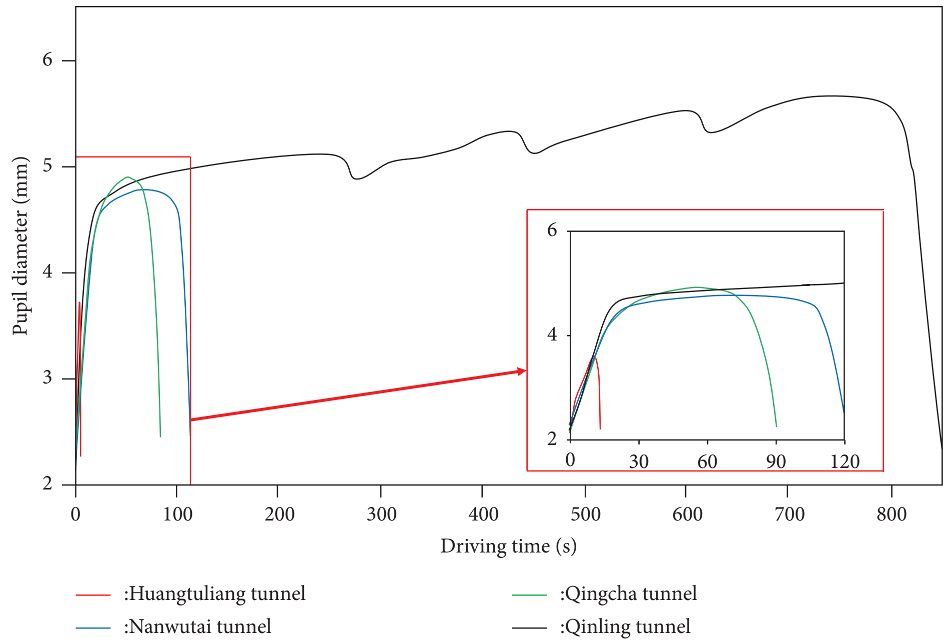

FIGURE 5: Pupil diameter changes of drivers in each tunnel.

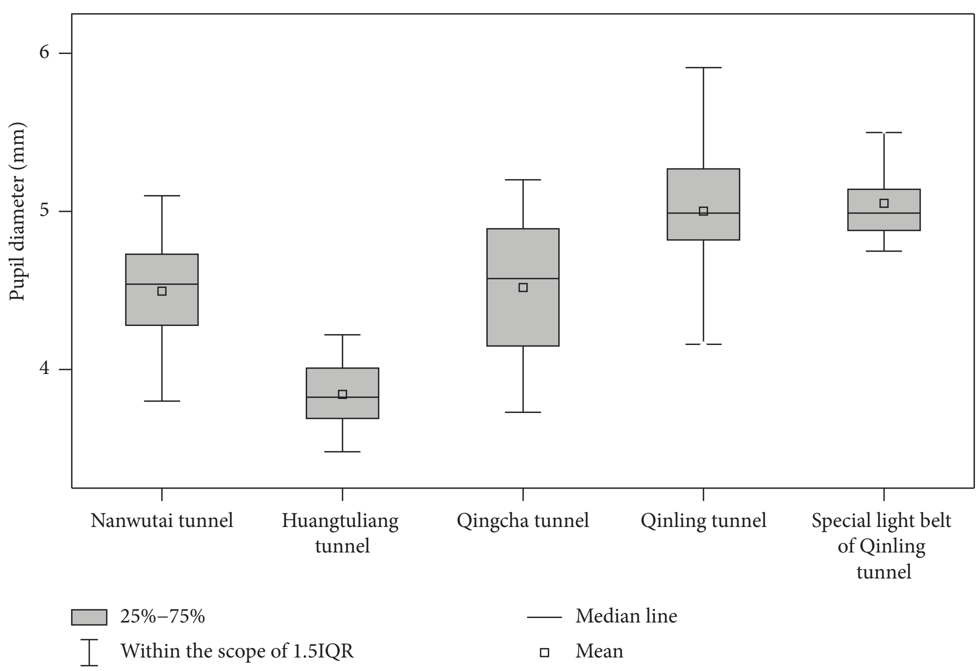

FIGURE 6: Box line graph of pupil diameters of driver in each tunnel.

tunnel was 30.23%, 11.42%, and 10.75% larger than those in the Huangtuliang, Nanwutai, and Qingcha tunnels, respectively.

The main reason for these results is that the pupil diameters of drivers gradually dilate in the interior zone. Figure 7 demonstrates the change process of the drivers' pupil diameters in the Qinling tunnel during the 60th to 120th seconds of driving, which is a gradual dilation at a rate of 0.0060 mm/s. The interior zone of the Qinling tunnel extends to at least 7.75 times the length of other tunnels, which means a longer driving time in the interior zone, and therefore, its impact on increasing the drivers' visual loads is amplified.

3.2. Comparison of Drivers' Fixation Duration in Tunnels with Varied Length. As shown in Figure 8, for the drivers' fixation in the Huangtuliang tunnel, the short-duration group exhibited the largest fixation proportion (0.66), and the long-duration group exhibited the smallest fixation proportion (0.10). The drivers in the Qinling tunnel possess the largest proportion of

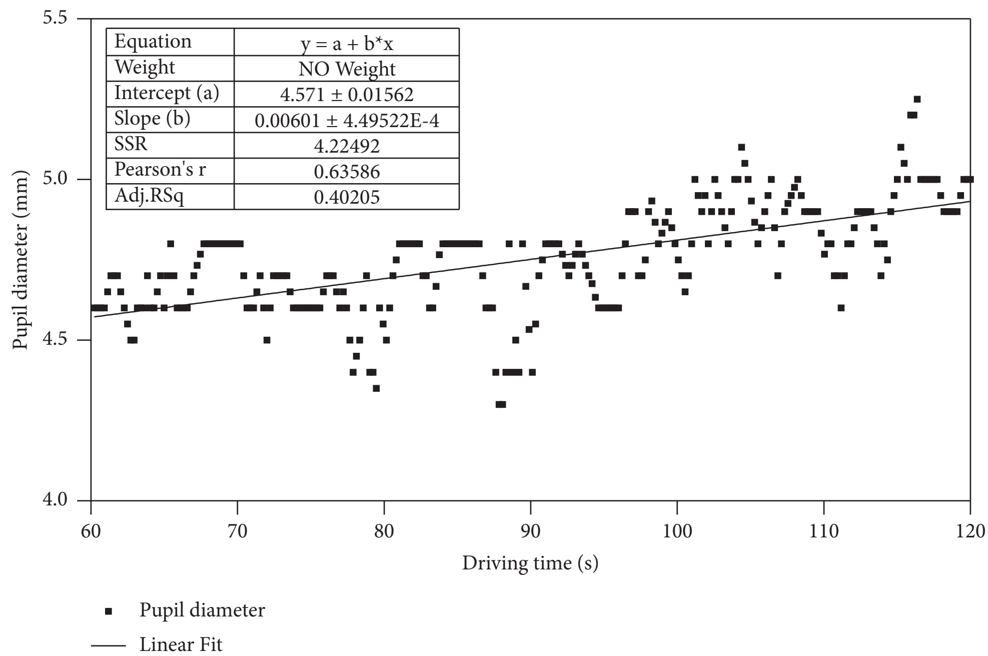

Figure 7: Drivers' pupil diameter changes during 60th to 120th second of driving in Qinling tunnel.

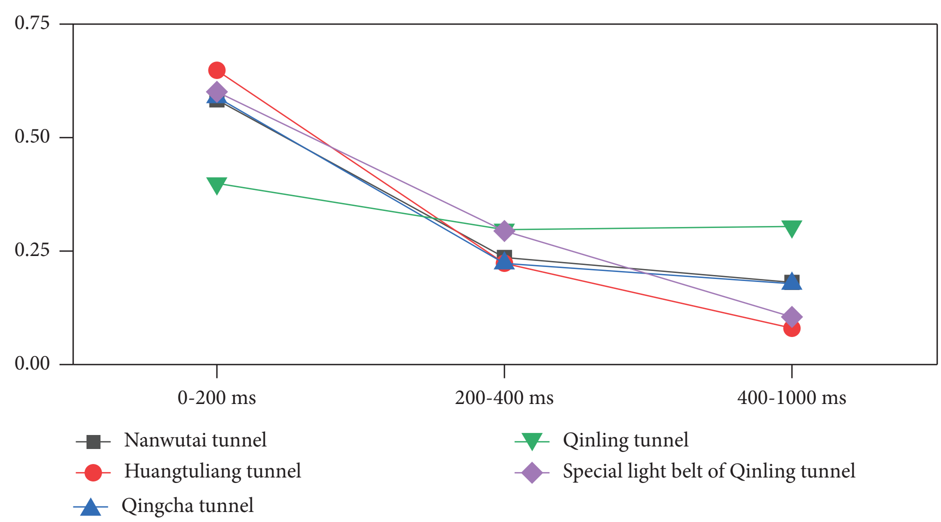

Figure 8: Proportion of drivers' different fixation duration in interior zone of each tunnel.

long durations, far surpassing those in other tunnels. This is mainly caused by the great length of the interior zone of the Qinling tunnel, which results in the long driving durations in a monotonous lighting environment, causing rigid driving behaviour, semiconsciousness, and longer time required to perceive targets. Therefore, the difference in length has an evident impact on the fixation duration of drivers. In extra-long tunnels of over 10 km, drivers exhibited lower visual efficiency and higher visual loads.

3.3. Comparison of Drivers' EEG Signal in Tunnels with Varied Length. In Figure 9, the graph of activated scalp areas by the power spectrum of the four frequency bands shows that, among all areas, those with the largest differences are those with the C3 and C4 electrodes. These electrodes correspond to the physiological sensing function centre of the brain, indicating that the accumulated driving time in tunnels exerted a substantial impact on driver soberness [23]. Figure 10 reveals that the average $(\theta + \alpha)/\beta$ of drivers in the Qinling tunnel was 3.82 μv^2, which is 15.44%, 40.91%, and 18.37% greater than those of the Nanwutai tunnel (3.31 μv^2), Huangtuliang tunnel (2.71 μv^2), and Qingcha tunnel (3.23 μv^2), respectively.

These experimental results demonstrate that the lighting environment of tunnels exerted a negative impact on driver soberness; the longer the tunnel, the less sober the driver.

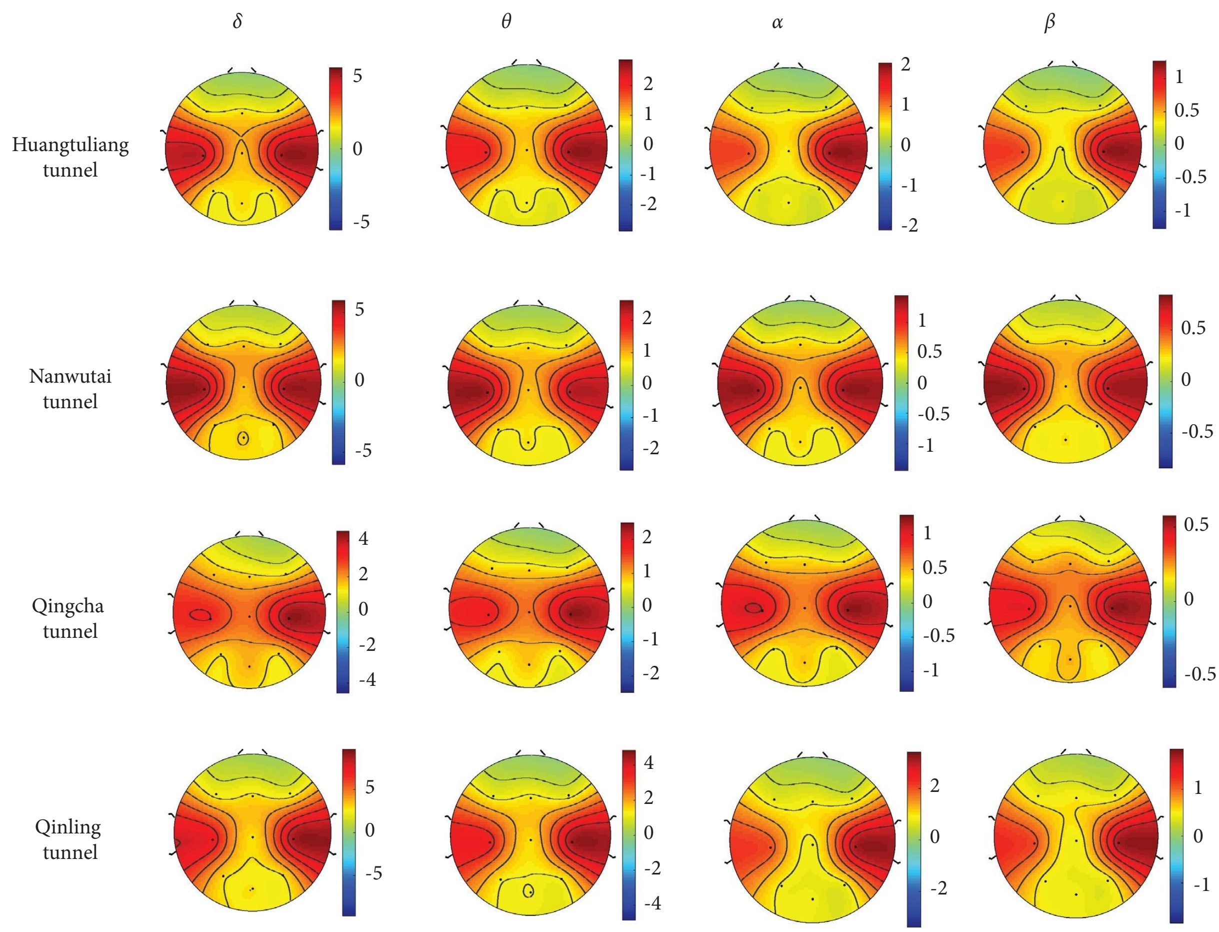

Figure 9: Topographic maps of drivers' brains.

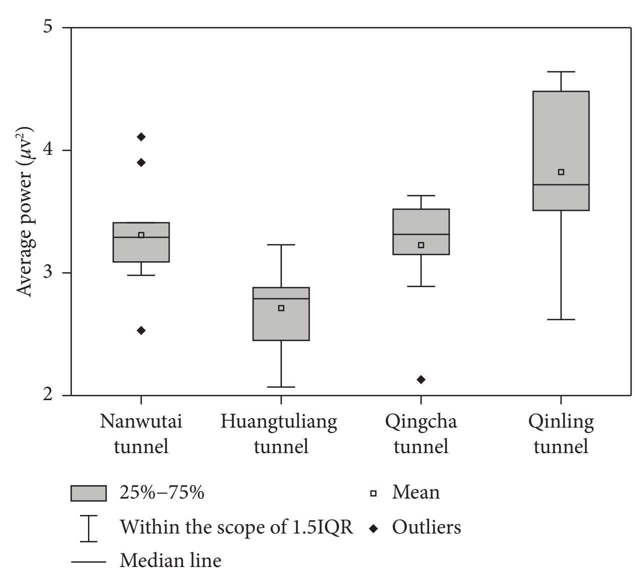

Figure 10: Drivers' EEG power changing pattern.

3.4. Comparison of Drivers' SDNN in Tunnels with Varied Length. Figure 11 illustrates that the SDNN value increases with the driving time, but their increments are different. The SDNN of drivers in the Huangtuliang tunnel shows only a growth of 0.19 ms throughout the entire driving process, whereas those in Nanwutai and Qingcha tunnels show a linear growth and only increased by 0.36 ms and 0.30 ms, respectively. Conversely, the changing pattern of the SDNN in the Qinling tunnel is different. In the first two driving zones, the drivers passed the entrance section and entered the interior zone, with the SDNN remaining within a low range. However, as the driving time increases, the SDNN exhibits an explosive growth of 1.94 ms in the third and fourth zones. When the subjects drove through the first special light belt, the SDNN dropped gradually by 0.01 ms between the two special light belt zones, indicating that the tension of the drivers was alleviated to some extent. However, as the driving time in the interior zone increased, the SDNN started to grow again in the 7th driving zone. The two subsequent special light belts exerted an inhibitive effect on the increase in SDNN. However, the indicator remained at a rather high level in the third to fourteenth zones.

As such, it can be found that the lighting environment of tunnels exerts a negative effect on driver tension, and when the driving time exceeds 180 s, the tension level increases rapidly. In previous studies, some scholars have shown that in a narrow environment, when the distance between the individual and the boundary decreases, their attention processing on the target object will be affected [24–27]. Research shows that in a closed environment, the experimenter needs to bear more pressure to complete the task, and with the increase of experimental time, there will be negative emotions such as anxiety for experimenter [28–30]. The lighting environment in the interior zone of the tunnel is characterized by semiclosure. In this environment, drivers need to bear more psychological pressure. At the same time, drivers in the interior zone of the tunnel should not only pay attention to the traffic coming from the front and rear but also pay attention to the distance between the vehicle and the side wall of the tunnel at all times. The visual task is also more onerous. Therefore, when the driving time accumulates to a certain extent, the drivers' SDNN index increases sharply.

3.5. Comparison of Drivers' RMSSD in Tunnels with Varied Length. Figure 12 shows the increasing trend of the RMSSD indicator for all drivers in different tunnels, each with a different pattern. After the drivers drive through the tunnels, their RMSSD in the Huangtuliang, Nanwutai, and Qingcha tunnels improved by 0.03, 0.01, and 0.01 ms, respectively. However, the RMSSD of the drivers in the Qinling tunnel exhibited a unique changing pattern—it increased rapidly after reaching a certain threshold. This is proven by the 1.77 ms growth in the third driving zone being far higher than the 0.75 ms growth in the previous zones. The growth rate of the RMSSD reveals that for long-term driving in the interior zone of tunnels, the increasing rate of drivers' visual loads is even greater than that for driving in short tunnels, where the lighting environment changes rapidly. Moreover, owing to the RMSSD threshold, the average RMSSD of drivers in the Qinling tunnel was significantly higher than that of drivers in other tunnels.

In summary, different psychological and physiological parameters indicate that drivers in the interior zone of extra-long tunnels of over 10 km bear a significantly higher visual load than those in regular tunnels. However, the values of these parameters and their changing patterns vary greatly; therefore, selecting only one indicator to measure drivers' visual loads will yield less reliable and incomprehensive results. Therefore, multiple indicators from multi-source information should be merged to create a comprehensive indicator for visual load evaluation. This method has great significance for the comprehensive reflection of drivers' visual loads.

4. Comprehensive Evaluation of Driving Visual Load Based on Improved Entropy Evaluation Method

In this study, indicators such as pupil diameter, fixation duration, $(\theta + \alpha)/\beta$ ratio, SDNN, and RMSSD were used to explain drivers' visual loads based on their ability to obtain visual information, visual efficiency, soberness, and tension levels during driving.

However, these psychological and physiological parameters provide varied indications of drivers' visual loads. Therefore, an increasing number of scholars have suggested integrating multi-source information to assess drivers' visual loads in the lighting environment of tunnels [16, 31]. This involves integrating multiple parameters and creating a comprehensive evaluation indicator for an all-inclusive and complete assessment of the drivers' visual loads.

The German scientist Rudolf Clausius first suggested the definition of entropy, which was developed into an entropy evaluation method for measuring the effective information in data. This method uses the uncertainty measurement feature of entropy to judge the effectiveness and values of existing indicators. A lower orderliness of an indicator means greater weight and vice versa [31, 32]. In this experiment, provided that the changing patterns of different parameters varied, the weights of each parameter at the entrance, middle, and exit sections were calculated. Finally, the comprehensive visual loads of the drivers were calculated based on the complete normalisation matrix.

The detailed calculation of the entropy evaluation method is listed below.

4.1. Data Normalisation. (1) The positive indicator is

$$X'_{\alpha ij} = \frac{X_{\alpha ij} - \min\left(X_{\alpha ij}\right)}{\max\left(X_{\alpha ij}\right) - \min\left(X_{\alpha ij}\right)} + 0.001, \tag{4}$$

and the negative indicator is

$$X'_{\alpha ij} = \frac{\max\left(X_{\alpha ij}\right) - X_{\alpha i}}{\max\left(X_{\alpha ij}\right) - \min\left(X_{\alpha ij}\right)} + 0.001. \tag{5}$$

(2) Indicator metrication: calculate the ratio of the jth indicator of tunnel i in the α-driving zone.

$$P_{aij} = \frac{X'_{\alpha ij}}{\sum_{\alpha}^{K}\sum_{i=1}^{M} X'_{\alpha ij}}. \tag{6}$$

(3) Calculate the entropy value of the jth indicator.

$$E_j = -\frac{1}{\ln_{KM}} \sum\nolimits_{\alpha}^{K} \sum_{i=1}^{M} P_{aij} \ln P_{aij}. \tag{7}$$

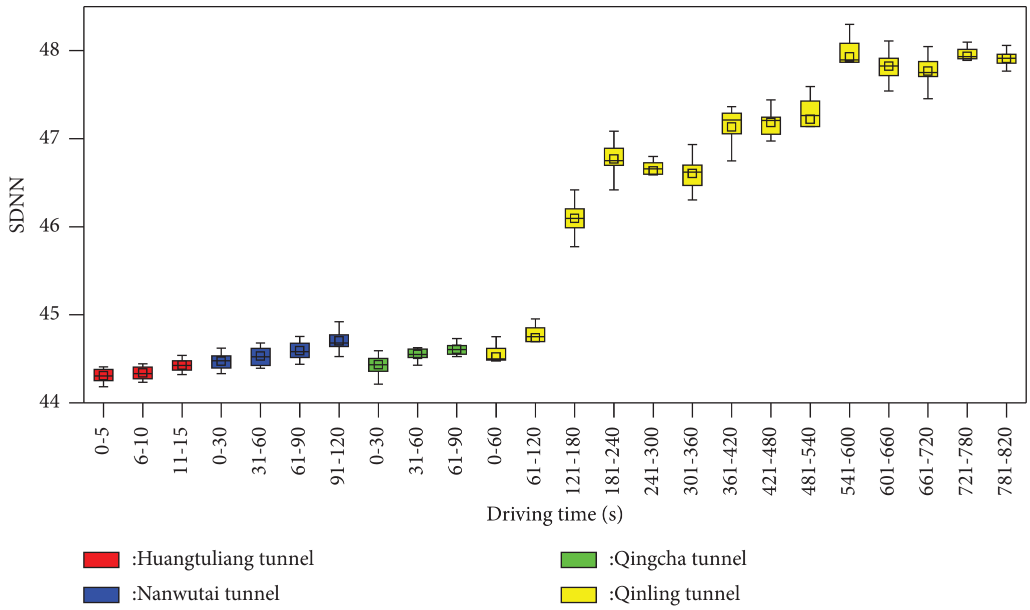

Figure 11: Changes in drivers' SDNN in each tunnel.

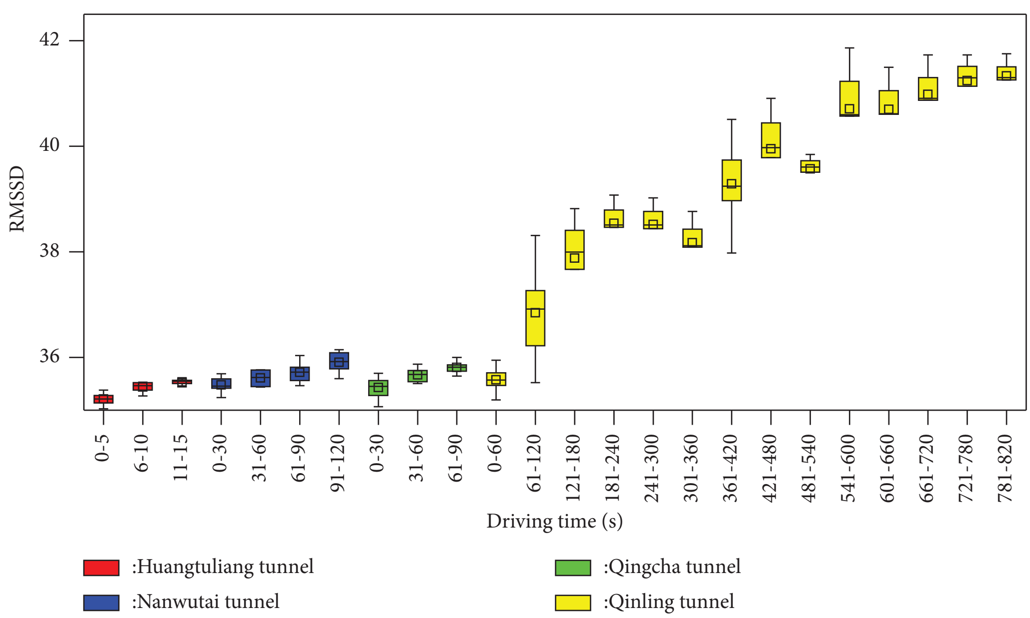

Figure 12: Changes in drivers' RMSSD in each tunnel.

(4) Calculate the entropy residual level of the jth indicator.

$$D_j = 1 - E_j. \tag{8}$$

(5) Calculate the weight of the jth indicator.

$$W_j = \frac{D_j}{\sum_{j=1}^{N} D_j}. \tag{9}$$

(6) Calculate the scores of each tunnel.

$$Z_{\alpha i} = W_j P_{\alpha i}. \tag{10}$$

In the above equations, $X_{\alpha ij}$ denotes the raw data of the jth indicator in αth section of the ith tunnel. The i values of 1, 2, 3, and 4 represent the Huangtuliang, Nanwutai, Qingcha, and Qinling tunnels, respectively. The j values of 1, 2, 3, 4, and 5 denote the pupil diameter, fixation duration, $(\theta + \alpha)/\beta$ ratio, SDNN, and the RMSSD, respectively; max $(X_{\alpha ij})$ and min $(X_{\alpha ij})$ represent the maximum and minimum values, respectively, of the $\{X_{\alpha ij}\}$ matrix.

4.2. Comparison of Drivers' Comprehensive Visual Load Features in Tunnels with Varied Lengths. As shown in Figure 13, the comprehensive visual loads of drivers increase as

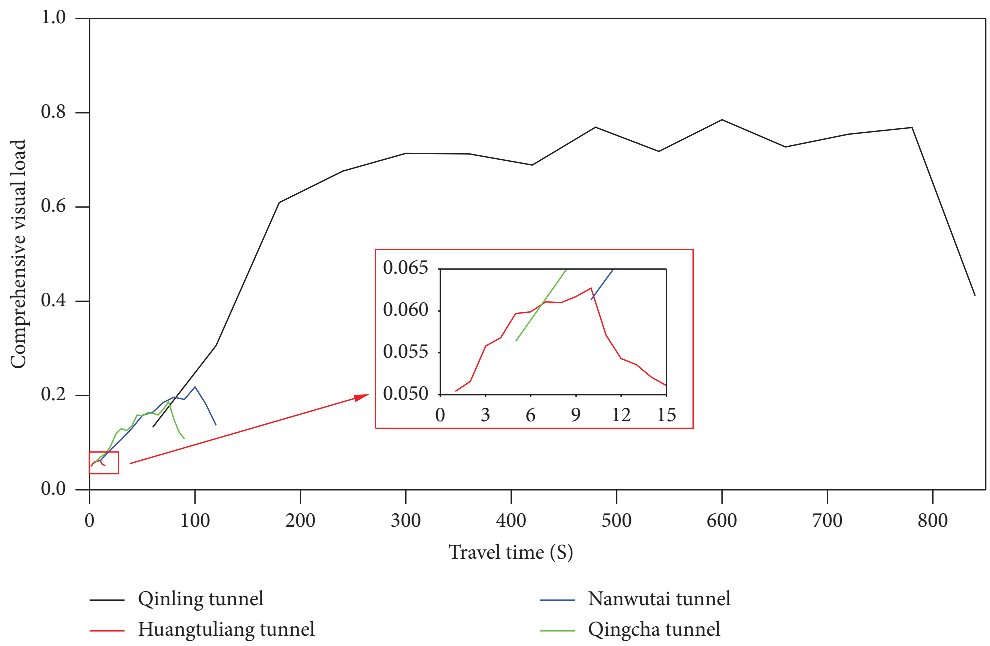

FIGURE 13: Changes in drivers' comprehensive visual loads in each tunnel.

drivers enter tunnels of varied lengths and decrease when drivers leave tunnels. Thus, it can be concluded that open spaces and bright environments can substantially lower the visual load of drivers.

Figure 14 shows the comprehensive visual loads of the drivers in the interior zone of the tunnels, which vary significantly. Consider the comprehensive loads of drivers in the interior zones of the Qingcha and Nanwutai tunnels as examples. The variance between the two comprehensive values is 15.38%. However, the differences between the two pupil diameters, fixation duration, and $(\theta+\alpha)/\beta$ were 0.45%, 1.22%, and 0.60%, respectively. Given that the length difference between the two tunnels is as high as 29.80%, the comprehensive visual loads acquired using the entropy evaluation method are more practical. If only one psychological or physiological parameter is used to evaluate drivers' visual loads, there is a high possibility of misjudgment.

5. Discussion

5.1. Relationships between Drivers' Comprehensive Visual Loads and Their Psychological and Physiological Parameters. The weight values of the psychological and physiological parameters differed significantly across all sections of the tunnels. Among all the parameters, the pupil diameter and fixation duration, with weight values of 0.25 and 0.30, respectively, in the entrance section exerted a largest contribution to the comprehensive visual load. In the interior zone, the SDNN and RMSSD, with weight values of 0.30 and 0.31, respectively, exerted a greatest influence on drivers' comprehensive visual loads.

In the entropy evaluation method, the weight values of the parameters were determined based on their differences. As the Huangtuliang tunnel is a typical nonoptical tunnel [33], the pupil diameter and fixation duration of drivers differ significantly from those of drivers in a long tunnel. This also suggests that improving the drivers' ability to obtain visual information and their visual efficiency at the entrance section should be a focus for future studies on the design and optimisation of tunnel lighting environments.

In terms of parameter differences in the tunnel interior zone, after driving for 180s, the SDNN and RMSSD values of drivers in the Qinling tunnel spiked; therefore, the SDNN and RMSSD of these drivers were more evidently different from those of the drivers in other tunnel interior zones. Therefore, to optimise the closed, monotonous, and dim lighting environments of the interior zone in extra-long tunnels of over 10 km, measures should be implemented to alleviate driver tension.

5.2. Design Optimisation for Extra-Long Tunnels over 10 km. The comprehensive visual loads of drivers in the interior zone of extra-long tunnels of over 10 km remained at a high level of 0.65, far surpassing those in the interior zone of other tunnels. In the safety evaluation of civil engineering, the likelihood-risk exposure frequency-consequence (LEC) method is usually used to assess the potential risks of a task, where L stands for the likelihood of accidents, E is the risk exposure frequency, C is the consequence possibly resulting from accidents, and the systemic risk value is the product of these three values [34]. In the interior zone of extra-long tunnels of over 10 km, drivers bear heavy visual workloads, and such tunnels are lengthier than regular ones; therefore, it is more difficult to perform a rescue if any accident occurs. Thus, academia in this field should focus on the important topic of improving the lighting environment of extra-long tunnels over 10 km to enhance driving safety and comfort.

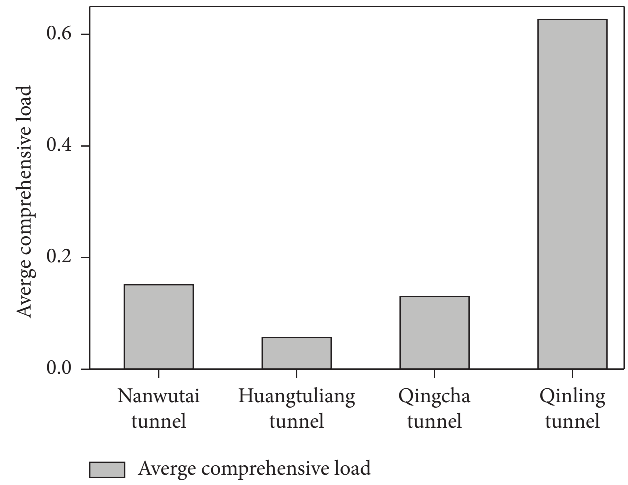

Figure 14: Changes in drivers' average comprehensive load in each tunnel.

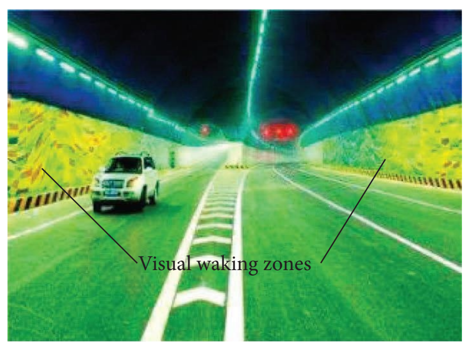

Figure 15: Visual waking zones on tunnel sidewalls [42].

As mentioned previously, the goal of improving the lighting environment of extra-long tunnels over 10 km is to alleviate driver tension. In the field of indoor illumination, some studies have found that the colour temperature of an environment affects people's emotions. Specifically, a high colour temperature was found to improve the stability of people's mood. Scholars in the field of tunnel lighting environments have attempted to improve the coating on tunnel sidewalls to enhance the colour temperature of the interior zone of tunnels. Some scholars discovered that power-saving reflective materials applied to tunnel sidewalls could improve the colour temperature of the light reflected on the sidewalls. Such materials mainly consist of silicate, which mostly reflects green light and can effectively ease the tension of drivers [35–39].

Researchers in the field of tunnel lighting have revealed a strong correlation between the luminance of the tunnel interior zone and driver tension. A luminance of 27 cd/m^2 can substantially relieve the driver tension [40]. Jiao et al. pointed out in a study of the lighting environment of extra-long tunnels' interior zone that setting up visual waking zones on tunnel sidewalls can reduce drivers' feeling of closedness caused by a closed environment, which is also an effective method to ease their tension [41] (Figure 15).

6. Conclusions

This study investigated the changing pattern of drivers' visual loads when driving in the interior zone of an extra-long tunnels over 10 km. The following conclusions were drawn:

(1) When driving in the interior zone of an extra-long tunnel of over 10 km, drivers bear high visual loads, which hinder their capability to obtain visual information and result in low visual efficiency, rigid driving, and high tension.

(2) Various psychological and physiological parameters of drivers reveal different aspects of their visual loads. The drivers' comprehensive visual loads acquired by integrating multi-source information using the entropy evaluation method can effectively assess the impact of accumulated driving time on their visual loads in a reasonable manner.

(3) The research results of the drivers' visual load features were used to guide the design and optimisation of the tunnel lighting environment. Considering that the design parameters of the special light belt are not specified in the current domestic and international lighting design specifications, in actual application, the length of the first section of the special light belt

from the portal is 3000~6800 m. However, the current research on the special light belt in the tunnel is more from the perspective of the alleviation effect of the high luminance characteristics of the special light belt on the drivers' visual fatigue. It is believed that the first section of the special light belt should be placed 1500~2000 m away from the tunnel portal, but this parameter design method ignores the frequent changes in the lighting environment that are likely to have an impact on the drivers' driving comfort. From the perspective of the restriction of the special light belt on the drivers' psychological tension, we believe that the first section of the special light belt should be placed 2500~4000m away from the tunnel entrance.

The optimisation of tunnel lighting environments based on the changing patterns of drivers' psychological and physiological parameters will be the focus of future research on tunnel lighting environments. This study focuses on comparing the change process of drivers' psychological and physiological parameters in tunnels of different lengths and discovers the visual load features of drivers in extra-long tunnels of over 10 km. It also discusses and combines the common measures for improving tunnel lighting environments and the experimental results in this study to offer general suggestions for future optimisation designs, which should be explored further in future studies.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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