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Research Article

Drivers' Eye Movement Characteristics in a Combined Bridge-Tunnel Scenario on a Mountainous Urban Expressway: A Realistic Study

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Combined bridge-tunnel scenarios of driving on mountainous city expressways occur when bridges and tunnels frequently alternate during driving. The complex nature of these driving scenarios imposes crucial requirements on the drivers' eye movement characteristics. This paper attempts to clarify these characteristics using descriptive statistics and the box graph method, registering the pupil diameter, blink duration, fixation, saccades, and fixation loci at different tunnel locations, bridges, and ramps. Realistic driving experiments were performed on the road segment spanning from the Nanchang tunnel to the Liujiatai tunnel freeway in Chongqing, China. Eye movement data were collected for 21 drivers. The experimental results showed that, while driving in the tunnel, the maximal pupil diameter of the participating drivers was approximately 4.0 mm as the driving mileage and the number of tunnels increased, and the maximal visual load on the drivers in the tunnel tended to be stable. At the second tunnel exit, the ramp, the middle section of the first bridge, and the third tunnel exit, the driving load was the highest, while the fixation duration was shorter for nighttime driving. The fixation duration was the longest for the diversion road of bridge B1 to the ramp during the day, and the fixation times were the longest at the beginning and end of the test road. The drivers more often paid attention to the speed dashboard while entering tunnels during daytime driving (compared with nighttime driving).

1. Introduction

The special geographical environment and geological conditions of mountainous cities necessitate the use of tunnel-type and elevated expressways on cross-river bridges between different city areas to shorten the driving distance and improve the road networks' efficiency, given that the traffic flows of multiple ordinary city roads converge to bridges and/or tunnels. With the increased construction of bridge-tunnel expressways connecting different city areas, defects associated with underground roads and surface traffic connection sections continue to highlight the significance of cross-river traffic pressure, demonstrating a "supply exceeds demand" situation [1]. Interchange spacing on mountainous city roads is narrow, and with many openings along the route, interchanges may become very complex [2]. The visual environment at the typical tunnel entrance and exit also may change significantly, which may induce temporary ocular blindness [3]. Bridges and interchanges are often connected by ramps for diversion purposes. When driving on bridges, it is necessary to choose driving lanes in advance according to the guidance provided by traffic signs, and an overload or a lack of relevant information when approaching a diversion ramp is likely to increase the drivers' recognition load and prevent from quickly detecting and processing driving-related information. In turn, this may lead to delayed or incorrect judgment of the drivers and may affect their driving decisions (such as those related to the speed control and lane changes in critical sections or making safe and timely lane changes), which may result in vehicle detours and reduced traffic efficiency [4]. As key components of any traffic network, bridges have limited length and are often connected to interchanges, which can easily affect downstream traffic efficiency in the case of congestions or accidents. The rescue time is long and difficult, which may seriously affect the driving safety [5]. On those road sections featuring both bridges and tunnels, congestions at the entrance to and exit from the tunnel are likely to affect the bridge traffic as well, resulting in reduced traffic efficiency, increased risk of accidents, and psychological pressure on drivers [6].

In a study on the eye movement characteristics and safe behavior of drivers on tunnel-featuring road sections, it was found that the drivers' visual responses were slower in monotonous driving environments [7]. The complexity of the driving environment may increase the physiological load on the driver. The ratio of the pupil diameter change, maximal instantaneous velocity of the pupil area, and duration of converted visual concussion are usually used for quantifying the drivers' state of adaptation to bright illumination [8]. Drivers are more aware of their surroundings when driving in tunnels at high altitudes, and the visual fixation is longer when driving in tunnels. When driving on plain areas, more attention is paid to the road ahead [9]. When a driver enters a super-long tunnel road section, the pupil area changes rapidly, and the driver's psychological state tends to stabilize and relax gradually [10]. The brightness level of the tunnel entrances and exits affects driving behavior and safety [11]. The tunnel walls can be decorated to modulate the driving environment-related information and improve the drivers' driving [12]. The longer the reaction time of a driver, the higher is the likelihood of an operational error, which in turn may lead to safety problems [13]. The entrance and exit of a typical tunnel are often asymmetrical, and different tunnel sections may exert different effects on drivers [14]. Driving in tunnels is more risk-prone; thus, there is an urgent need to develop strategies and actions for improving the drivers' awareness of tunnels' driving safety [15].

Among the different tunnel groups, the connecting areas exhibit the highest rate of collisions, followed by the entrance into the tunnel. At nighttime, the rate of accidents occurring in tunnels is lower than that in the other tunnel sections [16]. Currently, the recommended safety length threshold for the tunnel connection area is 100 m [17]. The level of visual adaptation at the upstream tunnel exit and the length of the connection are the main factors affecting the visual adaptation of drivers in the downstream sections of the tunnel and the entire tunnel group section [18].

A study on the cross-river bridge and tunnel connection sections of mountainous city roads found that the likelihood of drivers' repeated fixation is higher in tunnels, while their visual search efficiency is lower when driving in tunnels compared with driving on out-of-tunnel road sections. Drivers receive information mainly from straight-up front and straight-down front regions, and the likelihood of fixation in these two areas of the threshold and exit sections is significantly higher than that for other road sections [19]. When passing through a tunnel's entrance and exit, the rate of the increase in the pupil diameter varied significantly across the tested cohort [20]. As the driving time increased, the blink frequency increased, the blink duration increased, and the visual comfort of driving decreased [21, 22].

Many studies have addressed combined bridge-tunnel scenarios of mountain highways, but only a few studies have been conducted on the eye movement characteristics and operational safety of drivers for combined bridge-tunnel mountainous city driving scenarios. Although mountain city expressways (of relevance to combined bridge-tunnel driving scenarios) and mountain highways are both closed fast-driving environments, there are significant differences between them in terms of their external environments, structures and facilities, traffic composition, and traffic operation characteristics. The structure of a typical combined bridge-tunnel scene frequently changes, with rapid and repeated illumination changes experienced by drivers, and requires the drivers to exert more visual effort while driving on these roads. The eye movement characteristics in combined bridge-tunnel driving scenarios on mountainous city expressways remain elusive.

Therefore, this study considered a typical mountainous city combined bridge-tunnel scenario, spanning from Nanchang tunnel to Liujiatai tunnel in Chongqing City, for real-time vehicle testing. Eye movement data were collected in real time for test drivers. This study elucidates the distribution characteristics of the pupil diameter of the drivers in combined bridge-tunnel driving scenarios and changes in the blink, fixation, and saccade patterns, providing data support and a theoretical basis for tunnel lighting layout and traffic sign setting in mountainous city combined bridge-tunnel scenarios.

2. Methods

2.1. Participants. It is crucial to select the experimenters to increase the reliability and universality of the experimental results. The selection indicators involved the number, age, occupation, and gender of experimenters. Before determining the number of experimenters, the required sample size needs to be calculated by a reasonable statistical method using the expected variance, target confidence, and margin of error [23], as shown in the following equation:

$$n = \frac{Z^2 \sigma^2}{E^2}. \tag{1}$$

Here, n is the sample size; Z is the standard normal distribution statistics; σ is the standard deviation; E is the maximum error.

A significance level of 10% is chosen to reflect a 90% confidence level regarding the unknown parameter [24, 25]. When the confidence level is 90%, Z is equal to 1.25. σ ranges between 0.25 and 0.5. Due to the influence of traffic flow and test time on the test section, the value of σ is set to 0.36. E is equal to 10%, and thus, the required sample is 21. Therefore, the sample size is in line with the requirement. In order to statistically determine whether the number of subjects is sufficient for this study, twenty-one drivers were selected as naturalistic driving experiment participants, consisting of 16 males (76%) and 5 females (24%), and each subject had a valid Chinese driver's license with more than 2 years of driving experience, and the age range was from 24 to 45 years old (mean = 32.8; SD = 6.1) in this study. All subjects held a license and had 3–22 years of driving experience (mean = 9.9; SD = 4.6) who drove at least 6,000 km. All participants held a valid driver license, corrected visual acuity above 1.0, normal color vision, and stereovision, without refractive error, amblyopia, strabismus, or other ophthalmic diseases. Every participant had a good willingness to participate. The experiment complied with the ethical principles of the Helsinki Oath [26, 27]. SPSS 25.0 is used to perform a one sample *t*-test efficacy analysis. The results show that at the 90% confidence level, the statistical power of the sample size is 0.836, which is > 0.80. Then, gender was divided into 2 groups (male = 1, female = 2), age into 4 groups (0 for ≤25 years old, 1 for 25~35 years old, 2 for 35~45 years old, and 3 for ≥45 years old), the driving years into 3 groups (0 for ≤5 years, 1 for 5~10 years, and 2 for ≥10 years), and the mileage into 4 groups (0 for ≤100,000 km, 1 for 100,000~300,000 km, 2 for 300,000~500,000 km, and 3 for ≥500,000 km), the occupation is divided into 3 groups (0 for employees of state-owned enterprises and public institutions, 1 for professional driver, and 2 for freelancer). The independent sample Mann–Whitney *U* test and independent sample Kruskal–Wallis test were used to analyze the influence of five factors, such as gender, age, driving age, accumulated driving miles, and occupation, on the 'driver's pupil diameter in the starting point of the test. The progressive significance (2-sided test) was 0.313, 0.335, 0.484, 0.870, and 0.952, respectively, all greater than 0.05, indicating that the original hypothesis was valid, i.e., the test drivers' gender, age, driving years, mileage, and occupation had a significant effect on the pupil diameter of the drivers at the starting point of the test. The grouping of the five factors did not have a significant effect on the pupil diameter of drivers in the starting section of the test. Therefore, the sample size for this experiment can provide reliable answers to the studied questions.

2.2. Apparatus. The experimental equipment includes three parts, i.e., a dashcam, an eye tracker, and electric vehicles. The dashcam can record the driving process information with relatively high accuracy. The information is more comprehensive, ensuring the consistency between the time and location of the road section in the posttest. This can help determine the driving location and driving environment [28]. Furthermore, human mental activity is crucial and related to the spatial-temporal characteristics of eye movements, which are extracted by the eye tracker [29]. The eye tracker is an ultralight and robust noninvasive head-tracking module that ensures driver comfort and freedom of behavior [30]. The parameters, which are usually collected by eye trackers, include the fixation point, trajectory diagram, eye movement time, saccade direction, pupil size, and blink (Figure 1).

2.3. Experimental Road. In this study, from the Nanchang tunnel to the Liujiatai tunnel in Chongqing was selected as the experimental road. The length of the experimental road

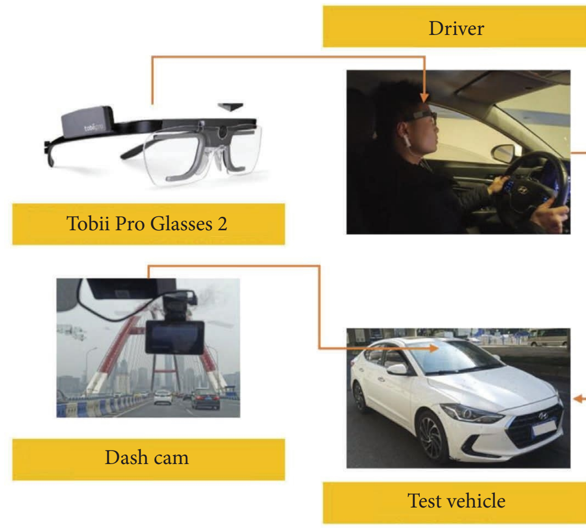


Figure 1: Test equipment and installation location.

is 8537 m, which is a tunnel-bridge-ramp connecting road. According to the Code for Urban Road Route Design (CJJ193-2012, China) [31], the Nanchang tunnel is 1,164 m long with a cross-sectional width of 10.5 m, a net height of 5 m at the building boundary, and 4-lane road. The main part of the Caiyuanba Yangtze River bridge is 800 m long, which is the main traffic road that connects Nan-An district and Yu-Zhong district. The upper deck of the bridge is a 2-way 6-lane urban expressway with a design speed of 60 km/h, and the lower deck of the bridge is a double-track urban railway of line 3 with a design speed of 75 km/h. The bridge and tunnel in Zeng-Jiayan has a total length of 5.54 km, with a designed speed of 60 km/h, which is the main traffic road that connects Jiang-Bei district and Yu-Zhong district. The standard width of the Zeng-Jiayan Bridge is 32.6 m, including 2 m sidewalk, 1.8 m stiffening stringers, 0.5 m crash barriers, 11 m carriageway on the left and right sides of the road, and a 2 m central divider in the middle of the road.

The bridge-to-tunnel ratio refers to the proportion of the mileage of bridges and tunnels to the total mileage, which is generally used in line engineering (railway, highways, and pipeline); a greater ratio of bridge-to-tunnel means a more difficult project. The ratio of bridge-to-tunnel of the experimental road is 88%.

The experimental road was classified into 6 parts according to type and quantity. The Nanchang Tunnel, Zeng-Jiayan Tunnel, and Liujiatai Tunnel are coded as T1, T2, and T3, respectively; the Caiyuanba Yangtze River Bridge and Zeng-Jiayan Bridge are coded as B1 and B2, respectively; and the Caiyuanba Ramp is coded as *R*.

The alignment and driving-related environment of the studied experimental road are shown in Figure 2, with bright lights and clear traffic markings. "Highway Tunnel Design Specification" (JTG 3370-2018) satisfied 3 s consistency requirements for tunnel entrance/exit plan alignment in China [32], while "Urban Underground Road Engineering Design Specification with Provisions" (CJJ 221-2015) stipulated that the flat and longitudinal alignments within the length of each

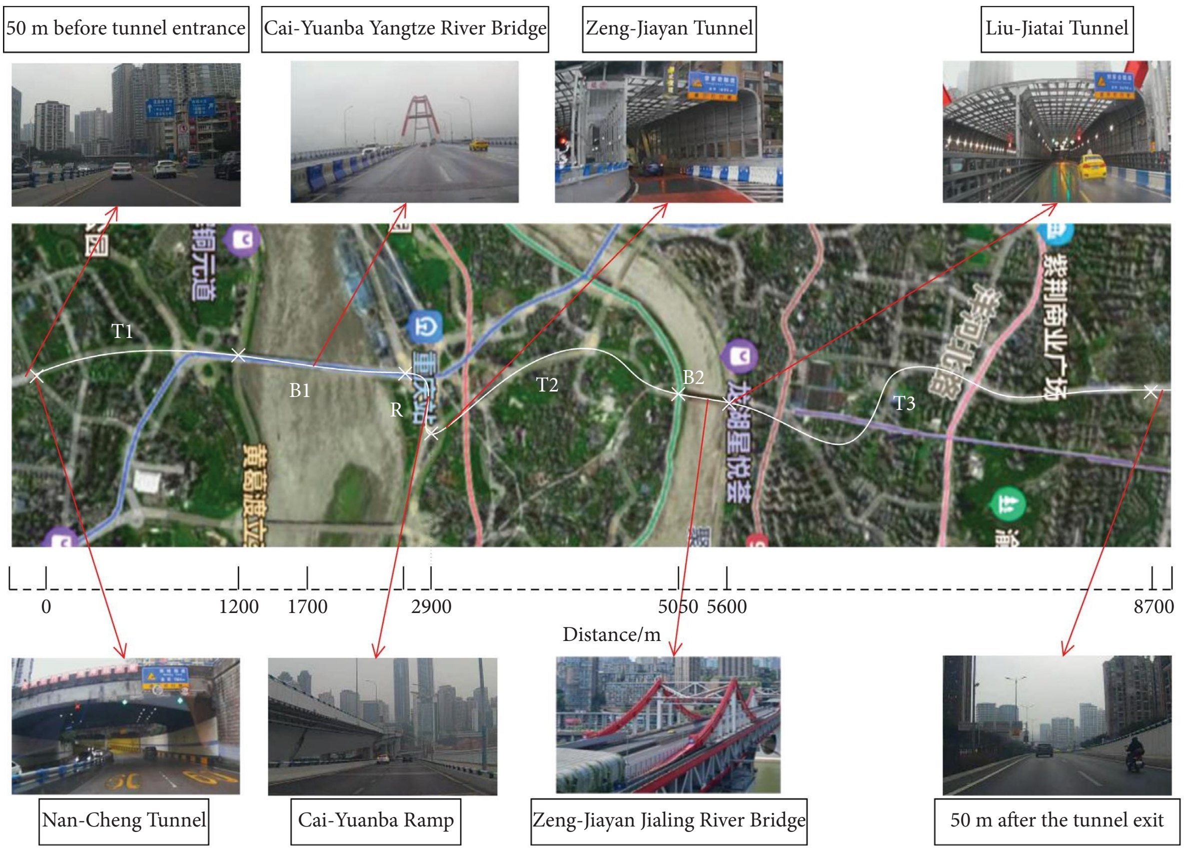


Figure 2: The alignment and driving environment of the experimental road.

3 s design speed travel inside and outside the urban underground road opening should be consistent; in difficult conditions, safety measures should be taken [33]. The design speed for the test section was 60 km/h, and the alignment of the tunnel entrance/exit within 50 m was calculated to meet the consistency requirements. Therefore, a detailed analysis of the eye movement characteristics 50 m before and after the tunnel entrance/exit was carried out in this study. Considering that the entrance into T1 tunnel is a signalized intersection followed by 6% of the underpass road entering the tunnel, drivers are significantly disturbed when driving, and the 50 m long road segment before the entrance into T1 tunnel was not included in the present analysis; only the 50 m long road segment immediately following the tunnel entrance was analyzed. The specific information is listed in Table 1.

2.4. Procedure. Before the experiment, check whether the experimental equipment such as the eye tracker is normal to avoid failure affecting the process during the experiment. The Tobii eye tracker was connected to the computer, and the visual calibration of the experimenters was performed to ensure that all parameters could be effectively collected. Make each driver perform a pretest, i.e., become familiar with the test route and test equipment. At the beginning of the formal experiment, the drivers followed their normal driving habits. The recording personnel pay close attention to the data collection of the recording platform of the eye tracker and remind and adjust the experimental equipment in time to ensure the data quality of the simulation experiment if the data collection is delayed or lost. After the experiment, sort and save the experimental data of each experimental driver. Figure 3 is the experimental flowchart.

3. Results and Discussion

Eye movement experiments are based on human visual analysis to infer human information processing and psychological cognitive processes. Human eye movements generally have three forms, such as fixation, blink, and saccades. The pupil diameter indicates the visual adaptability and load of drivers. With a shorter blink duration, the participants had to pay more attention to a more difficult task. Stern et al.believed that the longest blink duration was 500 ms, while there was no consistent conclusion about the shortest blink duration [34]. Benedetto et al. chose 70 ms as the minimum blink duration [35]. Mcintire et al. chose 80 ms as the shortest blink duration [36]. Fixation refers to the eye movement behavior that stays on the target object for more than 100 ms, the average fixation time represents the time it takes for a driver to process potentially dangerous information, or the ease of extracting valid information. Usually, the density of information in the fixation area and the ease of processing information directly affect the average fixation time. Saccades occur between two fixations of the human eye, and saccades are defined as the eye staying on

Table 1: Experiment-road information.

Designation	Number	Length (m)	Specific location	Location	Distance (m)
Nanchang tunnel	T1	1200	Entrance	T1-1	0~50
			Intermediate	T1-2	400~800
			Exit	T1-3	1150~1250
Caiyuanba Yangtze River bridge	B1	1000	Bridge-head	B1-1	1300
			Intermediate	B1-2	1700
			Bridge-tail	B1-3	1900
Caiyuanba ramp	R	833	Intermediate	R-1	2300
			Intermediate	R-2	2600
Zeng-Jiayan tunnel	T2	2090	Entrance	T2-1	2850~2950
			Intermediate	T2-2	3300~4700
			Exit	T2-3	5000~5100
Zeng-Jiayan Jialing River bridge	B2	550	Intermediate	B2-1	5300
Liujiatai tunnel	T3	2900	Entrance	T3-1	5550~5650
			Intermediate	T3-2	6000~8000
			Exit	T3-3	8650~8750
			200 m after tunnel exit	T3-4	8900
			500 m after tunnel exit	T3-5	9200

the target information for less than 100 ms. This indicator describes the process in which the driver searches for target information in the traffic environment [37].

In this study, we selected the eye movement indicators, including the pupil diameter, number of blinks, average blink time, number of fixations, average fixation time, total fixation time, number of saccades, and average saccade time, for quantitative analysis. Explore the inner psychological changes of the tested drivers when driving on the bridge and tunnel combination scenarios of mountainous urban expressways as shown in Table 2.

Due to the disturbance of driver activity and the occlusion of eye images during the experiment, there were problems of eye movement point loss and data anomalies, which were compensated by linear interpolation of signal packet loss, replacement of anomalous values, and noise reduction by a sliding mean filter. Ensure the quality of valid data, invalid data, such as blank data, duration greater than 75 ms, eliminate fixation durations less than 50 ms, and other failure data. Use the method of linear interpolation to compensate for experimental data with an acquisition blanking duration below 75 ms. Use sliding mean filtering and sliding root mean square filtering to reduce the noise of eye movement data.

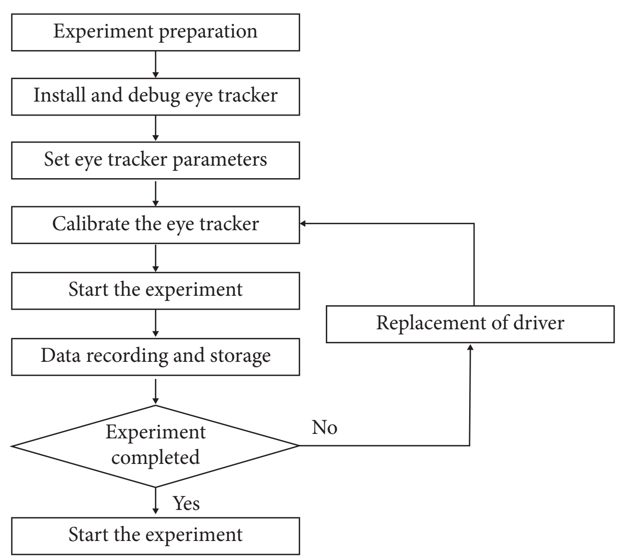


Figure 3: The experimental flowchart.

3.1. Descriptive Statistics of Pupil Diameter. The eye movement data of real drivers during the daytime flat peak period and free flow at night were collected through a real vehicle experiment. The pupil diameter test and descriptive statistical analysis were conducted for 6 structures, including T1–T3, according to the division of entrance, middle section, and exit, as shown in Table 3.

Changes in the pupil diameter at the tunnel entrance and exit sections are mainly caused by the changing luminance and involuntary physiological responses that are evoked for adapting to this switch in the drivers' external environment; consequently, pupil diameter changes have been used for characterizing the extent of the drivers' visual load. Under normal conditions, the mean pupil diameter of humans is 2–4 mm during the day and 5–7 mm at night [38]. Using the Origin software to plot the drivers' pupil diameter change curve, we determined that the average pupil diameter of daytime drivers decreased from 4.84 mm to 4.10 mm for the middle section of the tunnel, while the mean pupil diameter of nighttime drivers gradually decreased from 4.71 mm to 3.96 mm, as shown in Figures 4 and 5. The maximal pupil diameter gradually decreased with increasing driving mileage and number of tunnels, while the maximal visual load for driving in the tunnel gradually stabilized. During the day, the pupil diameter of the drivers increased rapidly when entering the tunnel and decreased linearly when leaving the tunnel. The pupil diameter was at a normal level for the other road sections. At night, the difference in the pupil diameters of the drivers between the road sections was not obvious, and

Table 2: Experiment index.

Eye movement	Unit	Meaning
Pupil diameter	mm	Direct expression of visual perception represents the degree of mental load of the subject
Blink count	N	BC reflects the degree of fatigue
Average blink duration	s	When sleepiness occurs, the blink rate becomes slower and the average blink duration becomes longer
Fixation count	N	The more the time of fixation, the more interested and important the information is in the area of interest
Average fixation duration	s	The time spent on each gaze is a factor of attractiveness, indicating the degree of interest of the subject.
Total fixation duration	s	Total fixation duration reflects the user's interest in information
Saccade count	N	Represents the attraction of an object
Average saccade duration	s	Refers to the time when the visual perception of the subject changes from perception to cognition
Viewpoint trajectory	—	It can fully interpret the behavior patterns of the subjects to help explore the psychological activities of the users

Table 3: Distance-pupil diameter information of the characteristic section.

Number	Distance (m)	Pupil diameter in the day (mm)			Pupil diameter at night (mm)		
		Average	Max	Min	Average	Max	Min
T1-1	0	2.97	5.08	2.02	4.64	5.5	3.54
	50	3.17	5.06	2.06	4.64	5.51	3.55
T1-2	400	4.83	6.18	3.81	4.71	5.48	3.71
	800	4.84	6.27	3.73	4.66	5.29	3.67
	1150	2.99	3.96	2.51	4.37	4.95	3.43
T1-3	1200	2.69	3.44	2.3	4.34	4.89	3.41
	1250	2.49	3.06	2.12	4.32	4.85	3.4
B1-1	1300	2.4	2.87	2.02	4.31	4.8	3.38
B1-2	1700	2.45	3.46	2.01	4.31	4.87	3.31
B1-3	1900	2.43	3.19	2.02	4.44	5.17	3.41
R-1	2300	2.45	3.11	2.02	4.72	5.55	3.92
R-2	2600	2.52	3.17	2.06	4.77	5.53	3.98
	2850	2.48	3.01	2.07	4.52	5.24	3.69
T2-1	2900	2.62	3.23	2.1	4.45	5.17	3.61
	2950	2.83	3.76	2.23	4.39	5.1	3.54
T2-2	3300	4.31	5.74	3.39	4.06	4.73	3.18
	4700	4.26	5.26	3.04	4.18	5.01	3.34
	5000	3.02	3.8	2.15	4.15	4.89	3.29
T2-3	5050	2.78	3.35	2.06	4.14	4.89	3.28
	5100	2.64	3.16	2.04	4.13	4.89	3.27
B2-1	5300	2.5	2.99	2.02	4.07	4.84	3.22
	5550	2.79	3.56	2.06	4.04	4.89	3.16
T3-1	5600	2.97	3.97	2.11	4.03	4.88	3.13
	5650	3.19	4.3	2.25	4.01	4.88	3.12
T3-2	6000	4.1	5.35	3.02	3.96	4.9	2.97
	8000	4.11	5.49	2.85	4.01	5	3.18
	8650	3.15	4.63	2.16	4.19	5.18	3.37
T3-3	8700	2.96	4.43	2.1	4.22	5.18	3.4
	8750	2.68	3.49	2.05	4.24	5.19	3.43
T3-4	8900	2.37	3.01	2.01	4.32	5.24	3.53
T3-5	9200	2.36	2.92	2.01	4.45	5.38	3.7

the visual load was high, which was affected by the lighting environment. Overall, the pupil diameter was more stable at night than during the day because the lighting of bridges and tunnels was similar at night, while there is a great difference between daytime tunnel lighting and sunlight on other roadways.

The pupil diameter was the largest and signaled a higher load for driving at nighttime on the ramp, which was owing to poor lighting conditions on both sides of the on-ramp and the inability to see the lane lines. The drivers relied only on the vehicle lights to ensure they drove in the right direction. To improve the safety of nighttime on-ramp driving, it is suggested to install reflective films on both sides of on-ramps and to enhance the recognition ability of drivers. Good lighting of a combined bridge-tunnel scenario at night can relieve the driving load of drivers.

When driving in the tunnel, the average pupil diameter was exhibited an "increasing-decreasing" trend at the entrance, middle, and exit road sections during daytime driving. However, the distribution of the average pupil diameter was more concentrated, without obvious regularity, for nighttime driving, as shown in Figure 6.

3.2. Blink Behavior Analysis. Increasing the difficulty of driving tasks would decrease the blink frequency and blink duration [39]. The blinking duration is a sensitive and reliable index to determine the drivers' visual load, and the frequency of blinking duration distribution of drivers under high mental load was 70–100 ms [40].

Figure 7(a) shows that the average daytime blink duration exceeded 100 ms for the road sections T2-3, R-1, and B1-2, while Figure 7(b) shows that the average nighttime blink duration was the longest for the road sections R-1, B2-1, and T3-3, that is, the drivers' driving load was higher for the second tunnel exit, ramp, middle of the first bridge, and third tunnel exit. This was because, when driving on the first bridge, the drivers' needed to select the driving lane ahead of time according to the traffic signs, and the guidance-related information before the diversion ramp was overloaded or lacking, increasing the load on the drivers. After identifying the correct passage onto the ramp, vehicles had to split and merge with traffic in the other directions on the ramp section. With increasing ramp traffic, gradually forming intertwined congestion at the diversion point, the shorter length of the intertwined area often created a traffic bottleneck point, and frequent lane changes and braking behavior increased the driving load. The second tunnel exit was at a short distance after the river bridge, and when driving in the tunnel, the middle space of the city tunnel was relatively closed, the sidewalls were mostly low-contrast white tiles, and the driving landscape was monotonous. Consequently,

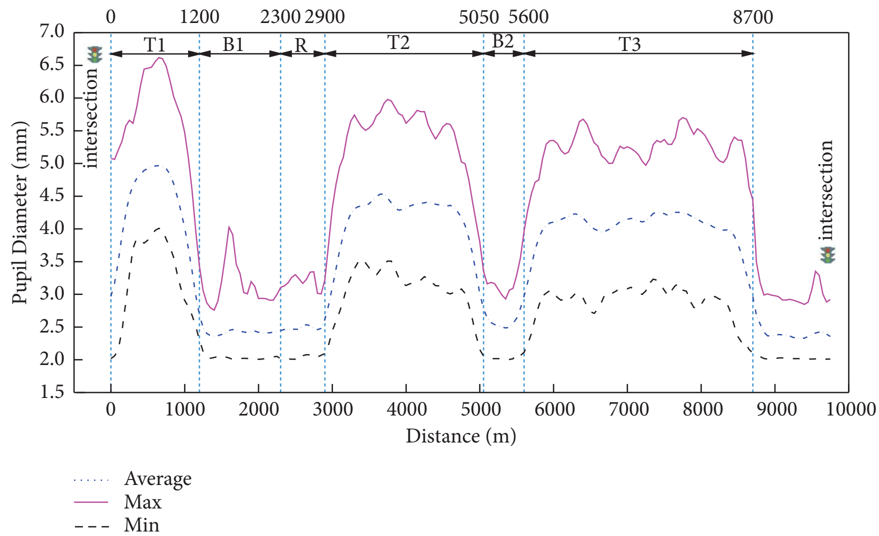


Figure 4: The daytime pupil diameter varies with distance.

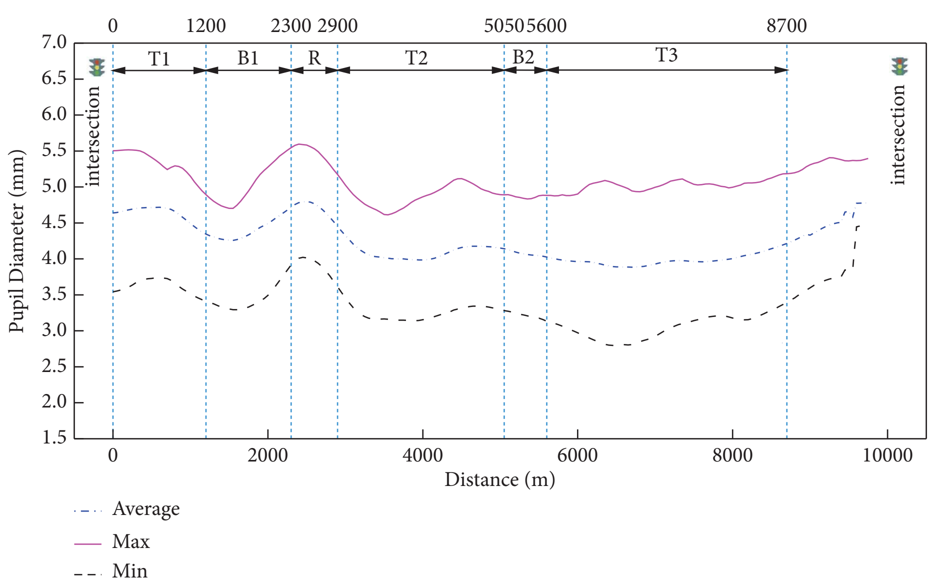


Figure 5: The pupil diameter varies with distance at night.

prolonged driving was more likely to trigger the spatio-temporal tunnel effect, leading to the drivers' fatigue or even discomfort, weakening their perception of the driving speed, headway time distance, and tunnel width. Driving out of the tunnel onto a short-distance bridge not only affected the drivers owing to differences in the external climate and environment but also frequently induced light and dark reactions. The connection between the super-long tunnel and short bridge could easily cause the drivers to experience the illusion of driving and thus increase their driving load [41]. Therefore, to alleviate the driving load on the drivers on the test section, it was necessary to set clear direction guidance signs and marking lines on B1 bridge, to reduce the difficulty associated with the direction identification, which reduced interweaving with traffic in other directions.

3.3. Fixation Behavior Analysis. The average fixation time for drivers familiar with the road section was short, ranging from one hundred and ten milliseconds to several seconds, and was influenced by the difficulty of the test and individual differences. Fixations that are too short or too long may be uncomfortable or confusing, respectively [42]. The fixation frequency and average duration for the middle tunnel during daytime driving were significantly lower than those for the entrance and exit, as shown in Figure 8(a). The fixation

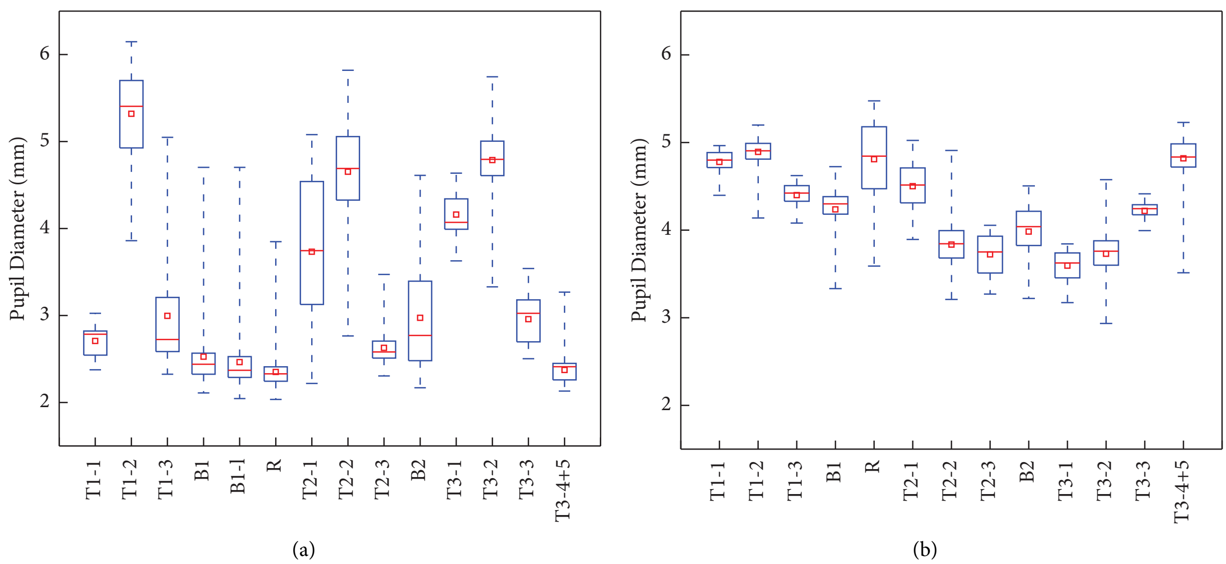


Figure 6: Box diagram of PD. (a) Day. (b) Night.

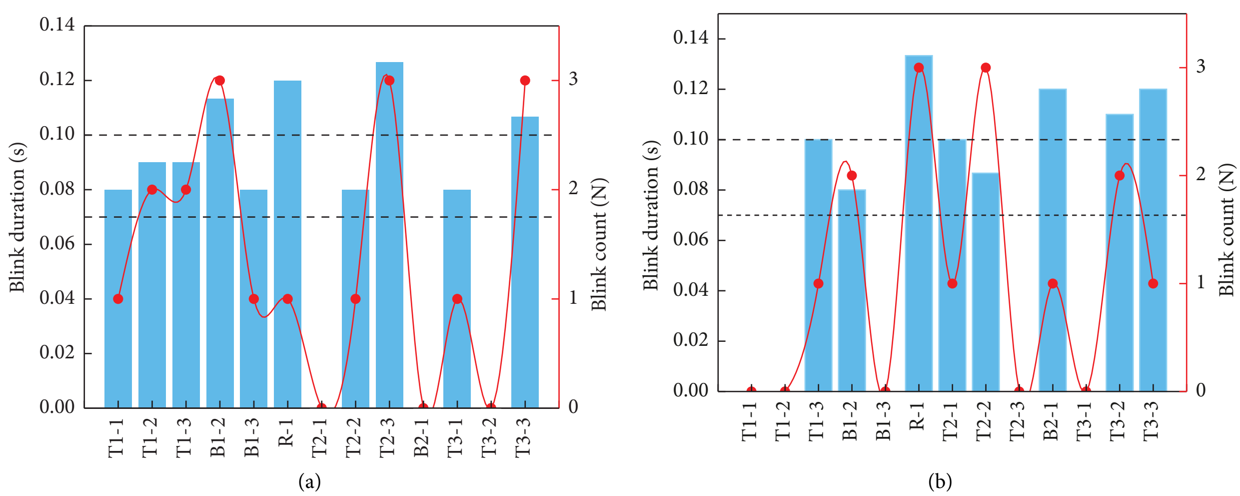


Figure 7: Blink behavior. (a) Day. (b) Night.

frequency and average duration for the tunnel entrance section were significantly lower than those for the middle and exit sections during nighttime driving, as shown in Figure 8(b).

The fixation duration for nighttime driving tended to be stable, the traffic flow at night was small, the surrounding traffic environment was familiar, and the fixation duration was relatively short. During the day, the fixation duration was the longest at the diverging section of B1 bridge, and the fixation frequency was the highest at the beginning and end of the test section, indicating that the drivers had to pay more attention at the beginning and end of the test section, to avoid accidents such as rear-end collisions. When driving into the entrance of tunnel T1 (slope, 6%), the drivers were prone to driving illusions, underestimating the true slope of the road, and not decelerating to the safe speed before entering the tunnel. At the end of the test section, the drivers experienced the space-time tunnel effect because sudden changes in the illumination environment at the tunnel entrance induced blind periods, causing the drivers to underestimate the actual driving speed, and thus fail to decelerate to the safe speed for driving on the main road. As a result, drivers were more likely to overspeed, creating a large speed difference between the tunnel traffic flow and the main road traffic flow. Along with the larger traffic flow on the main road and more complex lane changes, this contributed to the higher driving load.

3.4. Saccade Behavior Analysis. Saccades are quick searches of the visual field that serve to identify and pick up stimulus-related information; the average duration of a saccade episode is 20–40 milliseconds [43]. The more the saccades, the longer the search process. When a driver is fatigued, the perception of danger decreases, the number of saccades increases, and the ability to acquire stimulating

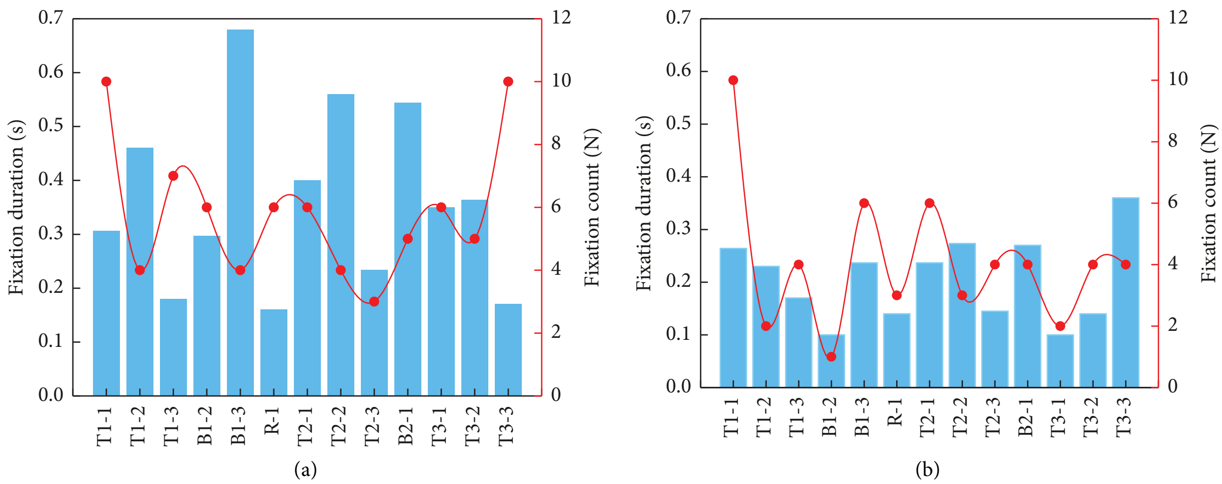


Figure 8: Fixation behavior. (a) Day. (b) Night.

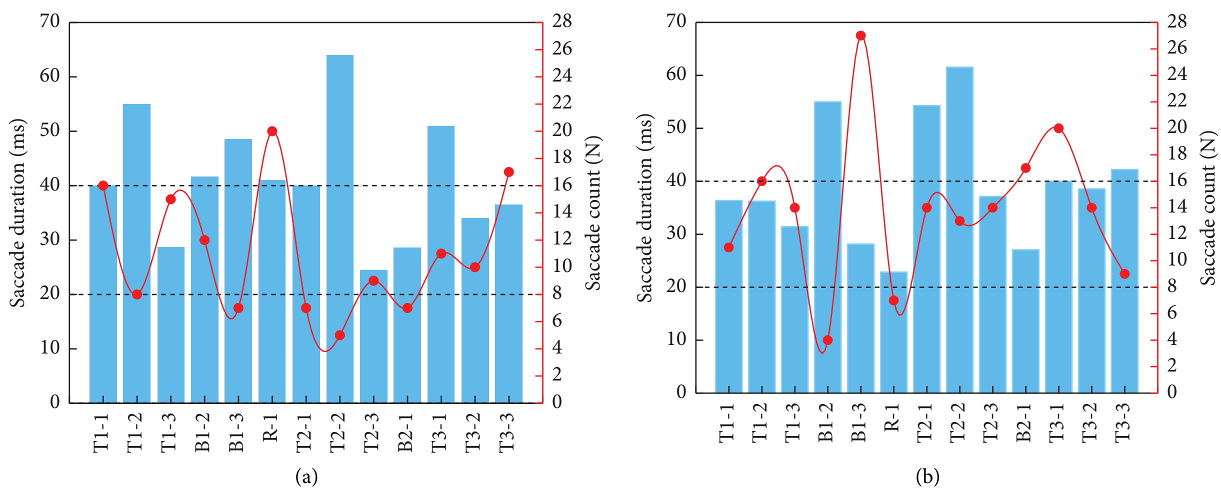


Figure 9: Saccades behavior. (a) Day. (b) Night.

spatiotemporal information decreases. Thus, saccade characteristics reflect the fatigue state of drivers to some extent. The number of saccades and mean duration of saccades in the middle section of the daytime tunnel were significantly lower than those at the tunnel entrance and exit, as shown in Figure 9(a). At night, the section connecting B1 bridge to ramp and B2 bridge to T3 tunnel was associated with the highest number of saccades, and the search process was longer, as shown in Figure 9(b). The number of saccades for nighttime driving fluctuated greatly and was significantly higher than those for daytime driving, indicating that the driving load associated with the bridge-tunnel section was higher and visual searching was longer during nighttime driving, which increased the drivers' fatigue.

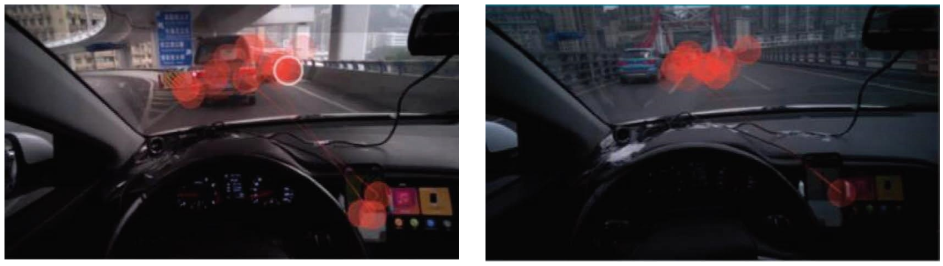
3.5. Viewpoint Trajectory. The viewpoint trajectory can clearly represent the driver's fixation behavior characteristics of obtaining road and target information when driving [44]. In this study, the trajectory and distribution of drivers' fixation points in 3 s before and after different positions are analyzed.

In the daytime, the drivers' fixation points were mainly distributed in front of the speed dashboard and driving lane in the three-tunnel entrance and exit sections of the experimental section. In the middle of the tunnel, the drivers' fixation points are more discrete and mostly distributed in the distant area of the driving lane. In the bridge, drivers' fixation points are mainly distributed in the far front of the speed instrument panel and driving lane. At the diverging point of the ramp, the driver's fixation point is mainly distributed in the navigation area of the mobile phone and near the front area of the driving lane, as shown in Figure 10.

At night, the drivers' fixation points are mainly distributed in the front of the driving lane in the three-tunnel entrance sections of the experimental section. In the middle of the tunnel, the drivers' fixation points are more discrete and mostly distributed in the distant area of the driving lane. At the tunnel exit, drivers' fixation points are distributed

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

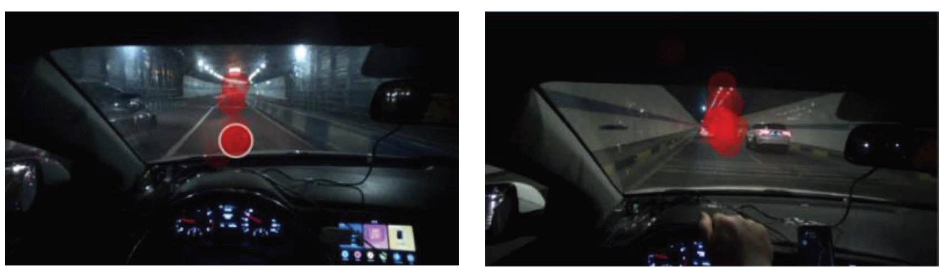
Figure 10: Continued.



(k) (l)

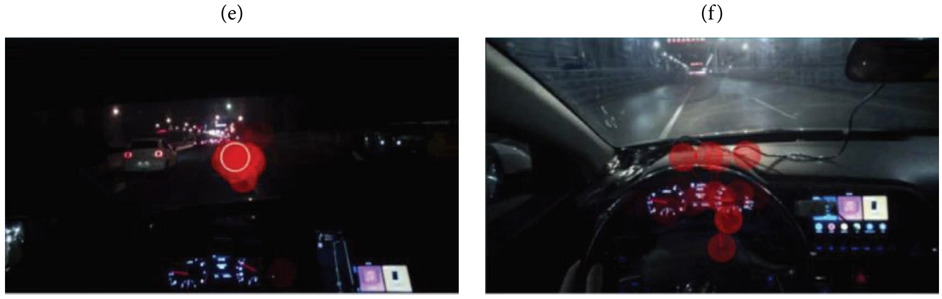
Figure 10: Gaze regions at different positions during the day. (a) T1-1 (0 m), (b) T2-1 (2900 m), (c) T3-1 (5600 m), (d) T1-2 (400 m), (e) T2-2 (4700 m), (f) T3-2 (6000 m), (g) T1-3 (1200 m), (h) T2-3 (5050 m), (i) T3-3 (8700 m), (j) B1-3 (1900 m), (k) R-2 (2600 m), and (l) B2-1 (5300 m).

(a) (b)



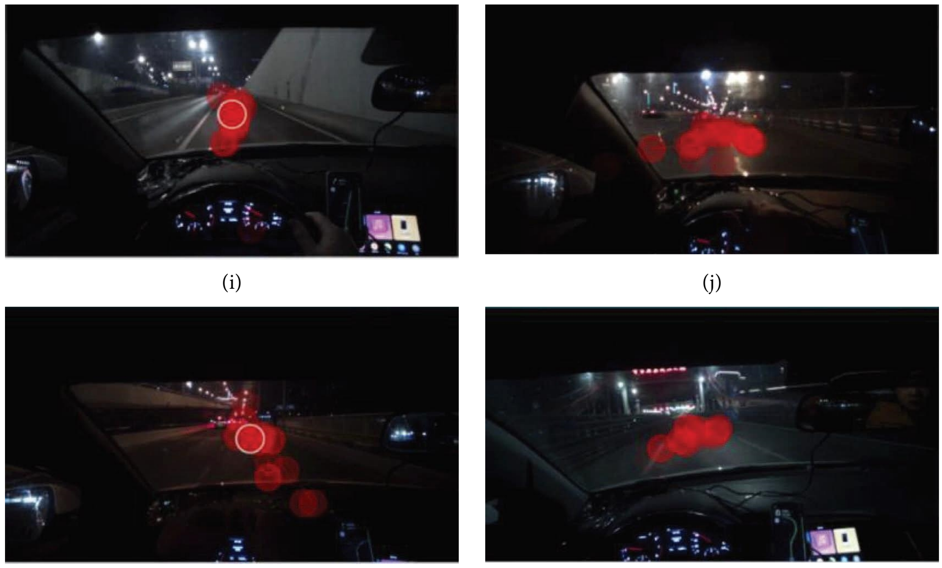
(c) (d)

(e) (f)



(g) (h)

Figure 11: Continued.



(i) (j) (k) (l)

Figure 11: Gaze regions at different positions during the night. (a) T1-1 (0 m), (b) T2-1 (2900 m), (c) T3-1 (5600 m), (d) T1-2 (400 m), (e) T2-2 (4700 m), (f) T3-2 (6000 m), (g) T1-3 (1200 m), (h) T2-3 (5050 m), (i) T3-3 (8700 m), (j) B1-3 (1900 m), (k) R-2 (2600 m), and (l) B2-1 (5300 m).

near the front of the driving lane. In bridges, drivers' fixation points are mainly distributed near the front of the driving lane. At the diverging point of the ramp, the driver's fixation point is mainly distributed in the navigation area of the mobile phone and near the front area of the driving lane, as shown in Figure 11.

Comparing the pilot fixation point distribution during the day and at night, the driver more often pays attention to the tunnel entrance section speed dashboard during the day than at night. The reason is that the daytime running condition is good, the drivers are at a larger speed, which easily exceeds the speed limit at the entrance to a tunnel, and the driver should be more focused on the velocity by considering whether to brake, to ensure safe passage within the speed limit. At night, lighting conditions on ordinary road sections are limited, the driving speed is low, and drivers pass at low speeds in tunnel entrances and exits to meet the speed limit requirements. Therefore, attention to the speed dashboard is not high. In the middle section of the tunnel, the fixation points change in a consistent way. At night, the drivers pay more attention to the area near the front of the driving lane.

4. Conclusions

The eye movement characteristics of the drivers, such as the pupil diameter, blink duration, fixation, saccade, and trajectories of fixation points, were analyzed using descriptive statistics and box graph methods. The variation rules of the drivers' eye movement indices were obtained for the combined bridge-tunnel scenario. The main conclusions are listed.

The drivers frequently experienced light and dark reactions. When driving through long tunnels and short bridge convergence sections, the drivers could not reasonably control the driving speed. In addition, the drivers often experienced driving illusions. In light of the above, to improve the safety of nighttime on-ramp driving, it is recommended to install reflective films on both sides of the on-ramp, which is likely to improve the drivers' identification ability. It is suggested to set up corresponding road markings to indicate lane information at the long tunnels and short bridge convergence sections, to add lighting facilities and passive luminescence inducement measures, to set up recommended speed signs, and to limit vehicle speed reasonably.

It is necessary to set clear direction guidance signs and lines on B1 bridge, to reduce the difficulty associated with the direction identification and the interweaving of traffic in the other directions when driving on on-ramp road sections. This study provides natural driving data for traffic departments to evaluate driving behavior and traffic safety control policies under the same scenario.

In this study, the combined bridge-tunnel scenario of driving on an expressway in a mountainous city was used as the experimental scene for obtaining relevant data, and the drivers' eye characteristic data were acquired at different times of the day and night. The effects of the combined bridge-tunnel scenario on the drivers' pupil diameter change, blink duration, fixation, saccades, and vision trajectory were analyzed. However, this study had some limitations. The study of the driving behavior in such scenarios allows to collect the drivers' physiological indicators, such as electroencephalogram and heart rate data, for improved driving in complex road scenarios.

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.

Acknowledgments

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