Research Article

Impact of Urban Undersea Tunnel Longitudinal Slope on the Visual Characteristics of Drivers

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This study aims to investigate the impact of the urban undersea tunnel longitudinal slope on the visual characteristics of drivers. 20 drivers were enrolled to conduct the real vehicle test of the urban undersea tunnel. First, the data of average fixation time and visual lobe were collected by an eye tracker. The differential significance was tested using the one-way repeated measures analysis of variance (ANOVA). Then, the difference between the up-and-down slope (direction) factor and the longitudinal slope (percent) factor on the two indexes were analyzed using the two-way repeated measures ANOVA. Second, by constructing a Lorentz model, the impact of the longitudinal slope on the average fixation time and the visual lobe were analyzed. Besides, a three-dimensional model of the longitudinal slope, average fixation time, and visual lobe was quantified. The results showed that the average fixation time and visual lobe under different longitudinal slopes markedly differed when driving on the uphill and downhill sections. The average fixation time and visual lobe under two factors were markedly different. Moreover, with an increase in the longitudinal slope, the average fixation time exhibited a trend of increasing first then decreasing; the visual lobe exhibited a trend of decreasing first and then increasing. The average fixation time reached the minimum and maximum value when the slope was 2.15% and 4.0%, whereas the visual lobe reached the maximum and minimum value when the slope was 2.88% and 4.0%. Overall, the longitudinal slope exerted a great impact on the visual load of the driver.

1. Introduction

Lately, the number of urban tunnels crossing rivers and mountains has gradually increased to adapt to the rapid development of the urban economy and regional expansion [1]. In coastal cities, the restrictions on the sea area have deferred the development of cities. Thus, in recent years, numerous special long undersea tunnels have been built, such as the Xiamen Xiang'an Tunnel (full length: 8.69 km) and Qingdao Jiaozhou Bay Tunnel (full length: 7.80 km), to accelerate regional economic development and shorten mileage. Typically, undersea tunnels have the characteristics of long distance, large longitudinal slope (usually 3%-4%), and high brightness of the hole (the effect of "black and white hole" is notable) [2]. Thus, compared with the general roads, undersea tunnels affect drivers' physical and psychological burdens in terms of long large uphill and downhill slopes

and poor sight [3]. Thus, exploring the visual characteristics of drivers in long large uphill and downhill slopes of undersea tunnels is of great significance to improve the traffic safety.

Currently, relevant research has not been conducted on the visual characteristics of drivers in the long and large slopes of undersea tunnel, and most studies have focused on highway tunnels and under-crossing tunnels. Regarding highway tunnels, Pan et al. analyzed the visual obstacles and driving visual comfort of drivers in highway tunnel entrance and exit using the pupil area maximum instantaneous velocity value (MTPA) as a visually compliant evaluation index [4]. Redenbo et al. and Macdonald et al. realized that the visual load was determined by both the visual physiological load and the visual perception load [5, 6]. Green et al. analyzed the factors influencing tunnel sight distance based on visual principles [7]. The study by Manser and Hancock

noted that drivers' perception of speed and their subsequent behavior will be affected by the visual mode due to the influence of the tunnel sidewall effect [8]. Regarding urban tunnels, based on real vehicle tests, Feng et al. proposed that drivers displayed the highest growth rate of the heart rate when driving uphill (longitudinal slope range, 3.5%–4.0%) and downhill (longitudinal slope range, 4.0%–4.5%) [9]. By comparing the visual information load of drivers on the ground and underground with the characteristics of vehicle operation, Chen and Zheng analyzed the influence mechanism of the visual environment of the underground road on the visual information load of the drivers [10]. By developing a multiple linear regression model among the heart rate, illumination, and vehicle speed at the entrance segment, Wu et al. investigated the impact of external factors on the heart rate [11]. Regarding long and large downhills, Yang et al. revealed that the drivers' pupil area was larger than other road sections in the black spot section of the long downhill road; the pupil area could effectively characterize the drivers' psychological stress, and the drivers were more sensitive to the left turn [12]. Through three different models, Gu revealed that when the downhill longitudinal slope was 3.7%, the eye movement speed was the smallest, and when the downhill longitudinal slope was 3.6%, the range of the gaze point was the smallest [13].

Above existing studies primarily focus on the analysis of the characteristics of the drivers' eye movement such as the gaze, saccade, and pupil changes in highway tunnels [14, 15] and urban tunnels [16, 17]. Unfortunately, relevant studies on the drivers' visual characteristics in urban undersea tunnels is lacking at this stage. Thus, this study aims to analyze the drivers' visual characteristics at long and large downhill sections in urban undersea tunnel and provide an effective theoretical basis for the safe operation of urban undersea tunnels.

In this study, the drivers' eye visual data were collected in the Jiaozhou Bay undersea tunnel via the real vehicle test, and the drivers average fixation time and visual lobe data were analyzed. Besides, the correlation among longitudinal slope, average fixation time, and visual lobe was explored to assess the visual load of the drivers in the undersea tunnel section. To achieve the objectives of this study, the following issues must be addressed:

(1) Does a significant difference exist in the driver visual data when driving on a different longitudinal slope in the tunnel?

(2) Does a quantitative relationship exist between the longitudinal slope and the visual parameters such as the average fixation time and the visual lobe?

(3) Is there any difference in the eye movement behavior and psychological load when driving at the uphill and the downhill section?

2. Test Design

2.1. Test Road. In the real vehicle test described in this study, the Qingdao Jiaozhou Bay Tunnel was selected as the research object (Table 1). It is a divided tunnel, and cars in different directions do not interfere with each other. The starting and ending points of the test were the Huangdao Toll Station of the Jiaozhou Bay Tunnel.

2.2. Participants. The participants were required to have, at least, 3-year experience in the driving age, owing to the particularity of urban undersea tunnels and to ensure the safety. Besides, the participants were not achromatopsia and hypochromatopsia, and their visual acuity was normal or corrected-to-normal; the participants had no psychological and physical defects; and the participants did not experience any major traffic safety accidents. Overall, 20 participants (14 males and 6 females) were included in the study. Their average age was 33.850 years (SD = 6.952), while their average driving experience was 6.905 years (SD = 3.987). All participants got paid (300 RMB) after the tests. Table 2 presents the basic information about the participants.

2.3. Test Equipment and Vehicle. The eye tracker used in the tests was a head-mounted Dikablis Professional eye tracker (Ergoneers GmbH, Geretsried, Germany) with the following characteristics: sampling rate, 60 Hz; pupil tracking accuracy, 0.05; sight tracking accuracy, 0.1°–0.3°; scene camera, 1920 × 1080 Full HD; and scene camera range, 40°–90°. The eye data collection and postprocessing of the participants were performed by the equipped D-Lab software version 3.54 (Ergoneers GmbH, Geretsried, Germany). Eye movement recording was performed on a Dell laptop with Intel Core i7 2.7 GHz CPU, 16 GB memory, Nvidia Quadro M200M graphics card 1920 × 1080 pixels of screen resolution, and Windows 10 operating system. The test vehicle was a Chevrolet Cruze automatic 5-seater; and other devices included a Digital Video and car power supplies. Figure 1 shows the eye tracker and vehicle.

2.4. Test Method. To avoid the impact of subjective deviation and personal preference in the consciousness of experimenters and participants on the trial results, we adopted the double-blind principle and tried to evade other factors affecting the participants driving. Before the test, the drivers were informed with passing the test section based on their usual driving habits and following the traffic rules to freely travel the uphill and downhill tunnel sections. The specific steps of the test were as follows:

(1) The experimenter drives the test vehicle to the starting point and installs the equipment such as power supply and driving recorder.

(2) Before the formal test, the experimenter selects one participant to perform the pretest according to the established test plan to ensure that the test process is correct before conducting the formal test.

(3) Before the pretest and formal test, the experimenter cooperates with the participant to wear the eye tracker. The experimenter adjusted the eye tracker to the most comfortable angle of the eye tracker pupil lens and the scene lens under normal working

TABLE 1: The information of Qingdao Jiaozhou bay tunnel.

Item	Information
Length (m)	7800
Speed limit (km·h^{-1})	80
Lanes (m)	3×3.75
Longitudinal slope	0.3%–4.0%
Lighting facilities	LED

TABLE 2: Basic information of the participants.

The number of participants	Age	Driving age
20	22–46 years old	3–20 years
6 females 14 males	$M = 33.850$ SD = 6.952	$M = 6.905$ SD = 3.987

conditions, in order to decrease the impact on the participant due to the discomfort of the eye tracker;

(4) The experimenter cooperates with the participant to correct the participant's gaze point using the four-point calibration; after the correction, the experimenter specifies a place outside the car to let the participant look at it, following which the experimenter checks whether the participant's gaze point in the computer software D-Lab falls within the specified position; if no deviation occurred in the position of the gaze point after multiple checks, the test could be executed; if a deviation occurred in the position of the gaze point, the four-point calibration was rechecked, and the test was performed until the participant's fixation position was unbiased.

(5) During the test, the main experimenter constantly checked whether the eye tracker worked normally. If the equipment failed to work normally, the test data collection was stopped; after returning to the starting point, the participant was allowed to close eyes for rest in 5 mins before restart the test.

(6) To guarantee the reliability of test data, each participant repeated four times; every participant drove in the middle lane with the free-flow speed of 70–80 km/h; the tests were performed during low-peak periods at night (21:00–23:00).

2.5. Index Selection. The average fixation time and the visual lobe were selected to assess the driver visual characteristics in the long and large slope environment of an undersea tunnel. The visual parameters were obtained in different longitudinal slope environments to reflect the information extraction, collection ability, and visual load situation of drivers [18].

(1) Average fixation time:

The average fixation time is the average value of the driver's total fixation time divided by the number of fixation times in a certain period, also being a crucial index of visual characteristics. The long average fixation time suggests the more difficult the visual

information, the more the driver's eye needs to collect [19].

(2) Visual lobe:

The magnitude of the jump from the viewpoint between two adjacent gazes is defined as the saccade distance, being usually presented in degrees of the angle of view. In psychology, the concept of the visual lobe denotes the size of the visual recognition scope. It is easier to visualize when the search target exists within the scope of the visual lobe centered on the previous gaze point, while the target beyond this scope is difficult to visualize. Furthermore, the median value of the saccade distance is used to measure the visual lobe [20].

2.6. Data Collection and Preprocessing. We contacted the construction unit in advance to obtain the alignments. Before the test, the alignment data were combined with driving video to find some points of slope change in advance. After all the tests were completed, the task segments were divided in the D-Lab software. According to the information of mileages, slopes, markings, and signs, the points of slope change were identified to divide the slope task segments.

In order to prevent invalid data from affecting the results, the collected data were processed by the Pauta criterion. The calculation method of Pauta criterion was presented as follows:

$$|x_i - \overline{x}| > 3\sigma, \tag{1}$$

where x_i denotes the test data, $\overline{x}$ denotes the mean value of the data samples, and σ denotes the standard deviation of the data samples.

The threshold of the eye tracker for determining the fixation is 120 ms.

3. Test Results

3.1. Significant Difference Analysis. The task segments under different longitudinal slopes of the uphill and downhill sections were divided in the eye tracker supporting software D-lab. Finally, the visual data under different longitudinal slopes of the uphill and downhill sections were derived by the software.

Table 3 shows the mean and standard deviation of the average fixation time and the visual lobe under different longitudinal slopes of the uphill and downhill sections. Tables 4 and 5 show the results of one-way repeated measures ANOVA. Figure 2 presents a box line diagram of the average fixation time and visual lobe under different longitudinal slopes of the uphill and downhill sections. All data satisfied the Kolmogorov–Smirnov normality test ($P > 0.05$).

(a) Average fixation time:

First, based on the one-way repeated measures ANOVA, a significant difference test was performed on the average fixation time. It can be seen from the column Prob > ChiSq (Table 4) that the significance level ($1.1780E − 13$ and $5.518E − 13$) of average fixation time were <0.05. The assumption of sphericity

(a)

(b)

Figure 1: The eye tracker (a) and vehicle (b).

Table 3: The mean value of the average fixation time and visual lobe under different longitudinal slopes of the uphill and downhill sections.

	Uphill				Downhill			
Longitudinal slope (%)	Average fixation time (ms)		Visual lobe (°)		Average fixation time (ms)		Visual lobe (°)	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
0.30	314.405	20.351	3.946	0.308	315.071	26.067	2.934	0.264
1.302	298.414	18.802	4.010	0.281	290.897	18.802	3.054	0.278
2.15	275.190	17.288	4.054	0.331	263.190	17.288	3.145	0.381
2.23	272.103	17.221	4.192	0.424	265.103	17.221	3.186	0.413
2.47	267.987	18.467	4.650	0.475	281.021	18.466	3.234	0.449
2.88	279.043	24.766	4.674	0.538	290.043	24.766	3.453	0.500
3.45	305.502	24.674	4.109	0.522	325.969	35.785	3.254	0.487
3.50	313.026	33.121	4.010	0.508	327.060	33.120	3.220	0.533
3.90	329.418	42.814	3.604	0.450	341.751	52.432	3.039	0.482
4.00	330.981	70.542	3.621	0.306	345.014	70.542	2.966	0.371
Average	298.607		4.087		304.512		3.148	

Table 4: Mauchly's test of sphericity and evaluation of epsilon (one-way repeated measures ANOVA).

Index	Direction	Prob > ChiSq	Greenhouse–Geisser epsilon	Huynh–Feldt epsilon	Lower-bound epsilon
Average fixation time	Uphill	$1.1780E-13$	0.360	0.411	0.111
	Downhill	$5.518E-13$	0.409	0.476	0.111
Visual lobe	Uphill	0.066	0.706	0.925	0.111
	Downhill	0.351	0.714	0.940	0.111

Table 5: Tests of within-subject effects (one-way repeated measures ANOVA).

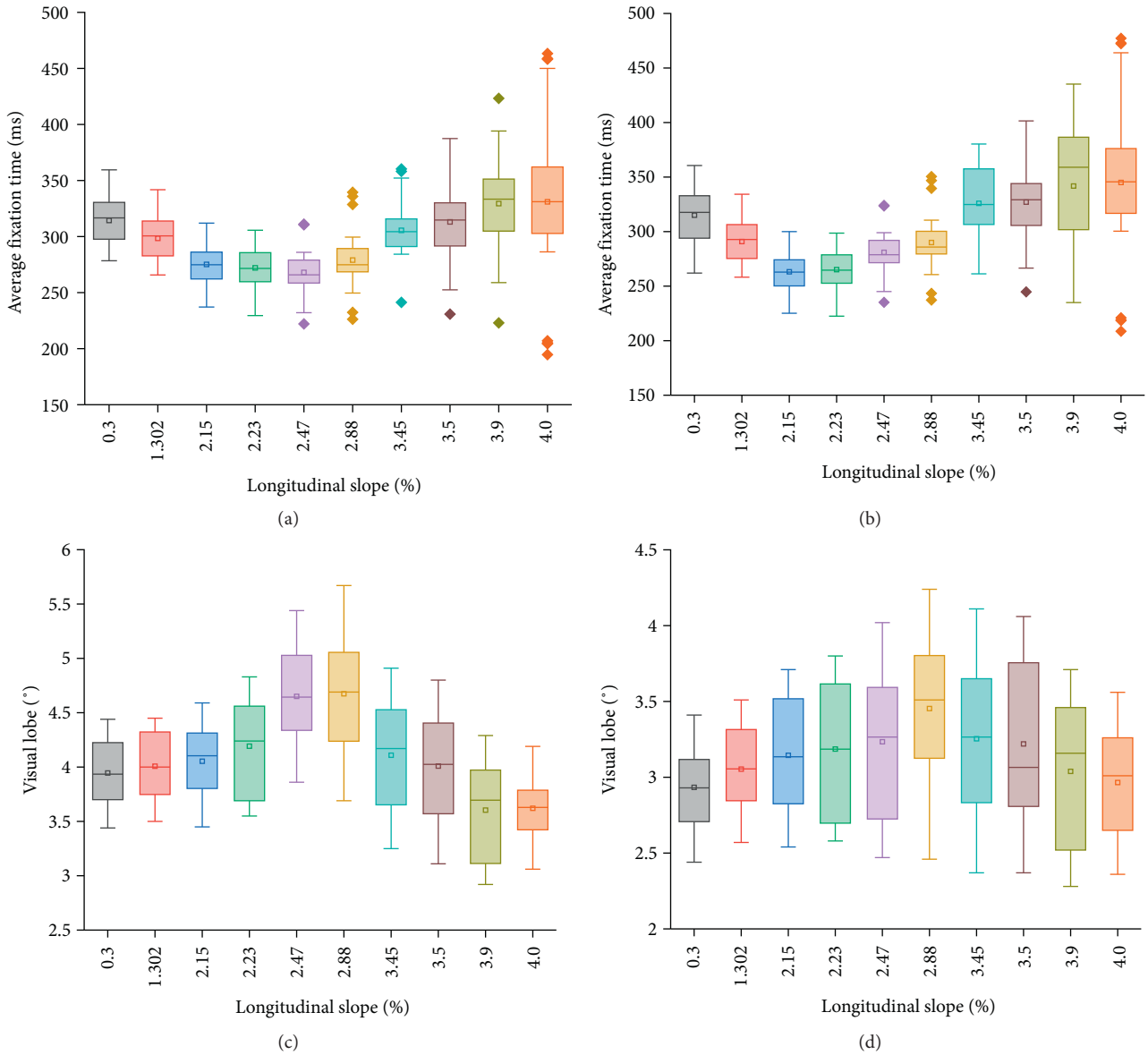| Index	Direction	Sphericity assumed		Greenhouse–Geisser epilon	
		F	Prob > F	F	Prob > F
Average fixation time	Uphill	15.693	$1.918E-20$	**15.693**	**9.688E − 9**
	Downhill	22.023	$1.208E-27$	**22.023**	**1.219E − 12**
Visual lobe	Uphill	**21.441**	**5.133E − 27**	21.441	$9.732E-20$
	Downhill	**3.983**	**8.817E − 5**	3.983	$6.580E-4$

FIGURE 2: The box plot of the average fixation time and visual lobe of drivers under different longitudinal slopes in the uphill and downhill sections. (a) The average fixation time under different longitudinal slopes in the uphill section, (b) the average fixation time under different longitudinal slopes in the downhill section, (c) the visual lobe under different longitudinal slopes in the uphill section, and (d) the visual lobe under different longitudinal slopes in the downhill section.

has been violated. The epislon of average fixation time were <0.75. Therefore, Greenhouse–Geisser correction was required. It can be seen, from the column Greenhouse–Geisser epsilon (Table 5), the uphill ($F = 15.693$, $p = 9.688E − 9$) and downhill ($F = 22.023$, $p = 1.219E − 12$) have significant difference under 10 different longitudinal slopes.

Meanwhile, the least significant difference (LSD) test was performed to analyze the significant difference of average fixation time under 10 different

longitudinal slopes conditions of uphill and downhill sections.

(1) When driving in the uphill section, the average fixation time at 2.15% (2.23%, 2.47%, and 2.88%) longitudinal slope was significantly <at 0.3%, 1.302%, 3.45%, 3.5%, 3.9%, and 4.0%. The average fixation time at 4.0% longitudinal slope was significantly> at 1.302%, 2.15%, 2.23%, 2.47%, 2.88%, 3.45%, and 3.5% longitudinal slopes, as shown in Figure 2(a).

(2) When driving in the downhill section, the average fixation time at 2.15% longitudinal slope was significantly <at 0.3%, 1.302%, 2.88%, 3.45%., 3.5%, 3.9%, and 4.0% longitudinal slopes. The average fixation time at 4% longitudinal slope was significantly> at 0.3%, 1.302%, 2.15%, 2.23%, 2.47%, 2.88%, 3.45%, and 3.5% longitudinal slopes, as shown in Figure 2(b).

(b) Visual lobe:

Second, based on the repeated measures one-way ANOVA, a significant difference test was performed on the visual lobe. It can be seen from the column Prob > ChiSq (Table 4) and the significance level (0.066 and 0.351) of visual lobe were >0.05. The assumption of sphericity has been satisfied. It can be seen, from the column sphericity assumed (Table 5), the uphill ($F = 21.441$, $p = 5.133E - 27$) and downhill ($F = 3.983$, $p = 8.817E - 5$) have significant difference under 10 different longitudinal slopes.

Meanwhile, the LSD test was performed to analyze the significant difference of the visual lobe under 10 different longitudinal slopes conditions of uphill and downhill sections.

(1) When driving in the section, the visual lobe at 2.47% and 2.88% longitudinal slopes was significantly greater than the visual lobe at 0.3%, 1.302%, 2.15%, 2.23%, 3.45%, 3.5%, 3.9%, and 4.0% longitudinal slopes. The visual lobe at 4.0% (also 3.9%) longitudinal slopes was significantly less than the visual lobe at 0.3%, 1.302%, 2.15%, 2.23%, 2.47%, 2.88%, 3.45%, and 3.5% longitudinal slopes.

(2) When driving in the downhill section, the visual lobe at 2.88% longitudinal slope was significantly greater than the visual lobe at 0.3%, 1.302%, 2.15%, 2.23%, 2.47%, 3.5%, 3.9%, and 4.0% longitudinal slopes. The visual lobe at 4.0% longitudinal slope was significantly less than the visual lobe at 2.23%, 2.47%, 2.88%, 3.45%, and 3.5% longitudinal slopes.

To further explore the impact on the average fixation time and visual lobe under the two factors of up-and-down slope and longitudinal slope, the significant difference levels of the two factors and the significant difference level between them were compared.

All data satisfied the normality test by the K–S normality test ($P > 0.05$).From Tables 6 and 7, the following can be obtained:

(a) Average fixation time:

Up-and-down slope (direction) ($F = 85.213$, $p = 3.925E - 10$) and longitudinal slope (percent) ($F = 18.728$, $p = 1.796E - 10$) have significant impact on the average fixation time. The interaction ($F = 34.322$, $p = 4.636E - 12$) between up-and-down slope (direction) and longitudinal slope (percent) was significant.

(b) Visual lobe:

Up-and-down slope (direction) ($F = 646.495$, $p = 2.245E - 21$) and longitudinal slope (percent)

($F = 18.754$, $p = 4.943E - 24$) have significant impact on the visual lobe. The interaction ($F = 5.611$, $p = 1.620E - 4$) between up-and-down slope (direction) and longitudinal slope (percent) was significant.

Combined with the overall mean values presented in Table 3, the average fixation time under the uphill factor was significantly smaller than the average fixation time under the downhill factor; the visual lobe under the uphill factor was significantly higher than the downhill factor.

3.2. Model Fitting Analysis.

To elucidate the correlation between the average fixation time and the visual lobe under different longitudinal slopes in the uphill and downhill sections, the data were analyzed by the curve fitting analysis via the OriginLab data analysis software. Fitting and comparison revealed that the Lorentz model has a good fitting effect, and the fitting formula is as follows:

$$y = y_0 + \frac{2A}{\pi} \frac{w}{4(x - x_c)^2 + w^2}, \qquad (2)$$

where y is the dependent variable, suggesting the average fixation time or visual acuity; x is an independent variable, denoting the slope of the reaction; y_0, A, π, w, and x_c are constants; and x_c is the positional parameter, denoting the position of the average fixation time or peak of the visual lobe under the longitudinal slope. Figure 3 shows the derived fitted curve of the average fixation time and the visual lobe.

Based on Table 8, the judgment coefficient R^2 and the corresponding P-value indicated that the fitting degree of the curves were excellent. Figure 3 and Table 8 revealed the following:

(1) When a driver drove in this tunnel, the average fixation time usually decreased first but then increased with the longitudinal slope. When the longitudinal slope was about 2.17% in the uphill section, the average fixation time reached a minimum of 270.194 ms. When the longitudinal slope was about 1.904% in the downhill section, the average fixation time reached a minimum of 265.830 ms.

(2) When a driver drove in this tunnel, the visual lobe usually decreased first but then increased with the longitudinal slope. When the longitudinal slope was about 2.685% in the downhill section, the visual lobe reached a maximum of 5.018°. Furthermore, when the longitudinal slope was about 2.916% in the uphill section, the visual lobe reached a maximum of 3.456°.

To illustrate the correlation among the longitudinal slope, the average fixation time, and the visual lobe, the data were analyzed using a 3D surface fitting analysis by using the OriginLab data analysis software. Fitting and comparison revealed that the Gauss2D model exhibited a good fitting effect. The fitting formula is as follows:

$$z = z_0 + A \exp\left\{ -\frac{1}{2}\left(\frac{x - x_c}{w_1}\right) - \frac{1}{2}\left(\frac{y - y_c}{w_2}\right)^2 \right\}, \qquad (3)$$

Table 6: Mauchly's test of sphericity and evaluation of epsilon (two-way repeated measures ANOVA).

Index	Direction	Prob > ChiSq	Greenhouse–Geisser epsilon	Huynh–Feldt epsilon	Lower-bound epsilon
Average fixation time	Up-and-down slope (direction)	≤0.001	1.000	1.000	1.000
	Longitudinal slope (percent)	$3.976E - 13$	**0.379**	0.436	0.111
	Interaction	≤0.001	**0.262**	0.287	0.111
Visual lobe	Up-and-down slope (direction)	≤0.001	1.000	1.000	1.000
	Longitudinal slope (percent)	0.079	0.705	0.923	0.111
	Interaction	0.034	0.688	**0.896**	0.111

Table 7: Tests of within-subject effects (two -way repeated measures ANOVA).

Index	Direction	Sphericity assumed		Greenhouse–Geisser epilon		Huynh–Feldt	
		F	Prob > F	F	Prob > F	F	Prob > F
Average fixation time	Up-and-down slope (direction)	85.213	$3.925E - 10$	85.213	$3.925E - 10$	85.213	$3.925E - 10$
	Longitudinal slope (percent)	18.728	$5.298E - 24$	**18.728**	**$1.796E - 10$**	18.728	$1.019E - 11$
	Interaction	34.322	$1.529E - 39$	**34.322**	**$4.636E - 12$**	34.322	$5.484E - 13$
Visual lobe	Up-and-down slope (direction)	646.495	$2.245E - 21$	646.495	$2.245E - 21$	646.495	$2.245E - 21$
	Longitudinal slope (percent)	**18.754**	**$4.943E - 24$**	18.754	$1.321E - 17$	18.754	$2.300E - 22$
	Interaction	5.611	$4.324E - 7$	5.611	$1.843E - 5$	**5.611**	**$1.620E - 4$**

where x, y, and z are variables and z_0, A, x_c, w_1, y_c, and w_2 are constant terms of the regression equation.

Based on Table 9, the judgment coefficient R^2 of the fitting curve and the corresponding P value indicated that the curve exhibited a good fitting degree. Figure 4 and Table 6 revealed the following:

(1) In the uphill section, when the longitudinal slope value was 1.89%, the maximum and minimum values of the visual lobe and the average fixation time were 4.67° and 239.85 ms, respectively.

(2) In the downhill section, when the longitudinal slope value was 2.04%, the maximum and minimum values of the visual lobe and the average fixation time were 3.45° and 258.68 ms, respectively.

4. Discussion

(1) The experimental data analysis focused on the relationship between the two indexes of average fixation time and visual lobe with the longitudinal slope. It is generally believed that, as the slope increases, the driver's visual performance is worse or the visual load is greater. However, Feng et al. [16] has discovered that the relationship between slope and heart rate growth was not linear. Heart rate growth reached the maximum at 3.33% and 2.91% of the uphill and downhill, respectively. However, a peak existed in the results of this test; thus, the longitudinal slope could be divided into three intervals by the regularity changing: slope <2%, 2% ≤ slope ≤3% (peak area), and slope >3%. Through the speed observation, the overall speed difference of the three sections was not significantly different (uphill, $p = 0.055 > 0.05$; downhill, $p = 0.078 > 0.05$). (1) In the interval where the longitudinal slope value was >3%, the average fixation time was the largest, and visual lobe was smaller. This section (especially the longitudinal slope was about 4%) was generally the tunnel entrance or nearly the entrance. Typically, vehicle speed increases in the long downhill section of tunnel entrance, and the drivers may need to step on the brakes [21] and stare at the dashboard to avoid speeding and rear-end collision. Meanwhile, for the uphill section, the drivers need to step on the throttle and gaze at the dashboard and rearview mirror because of the low speed in uphill section. Thus, the driver had numerous driving tasks and too much visual load on the large longitudinal slope section. In addition, the illuminance and the cross-section of the space that were changing dramatically at the entrance of the tunnel were highly dangerous or be psychologically nervous for drivers, which ultimately led to a marked reduction in driving comfort [15]. (2) In the interval where the longitudinal slope value was <2%, the driver's average fixation time was relatively large and visual lobe was smaller; this section was generally located in the middle of the tunnel, wherein the driving task and visual load were the smallest. However, the driver might experience driving fatigue when driving on a gentle section for a long time [22]. (3) In the interval where the longitudinal slope value was between 2% and 3%, the driver's average fixation time was the smallest and visual lobe was the largest; this section was generally located after a slope of >3% and <2%; the driver would be relieved from high visual load or driving fatigue. Furthermore, the slope perceived by the driver was just adapted to the driving state, at which time the driver was in a relatively low driving load state.
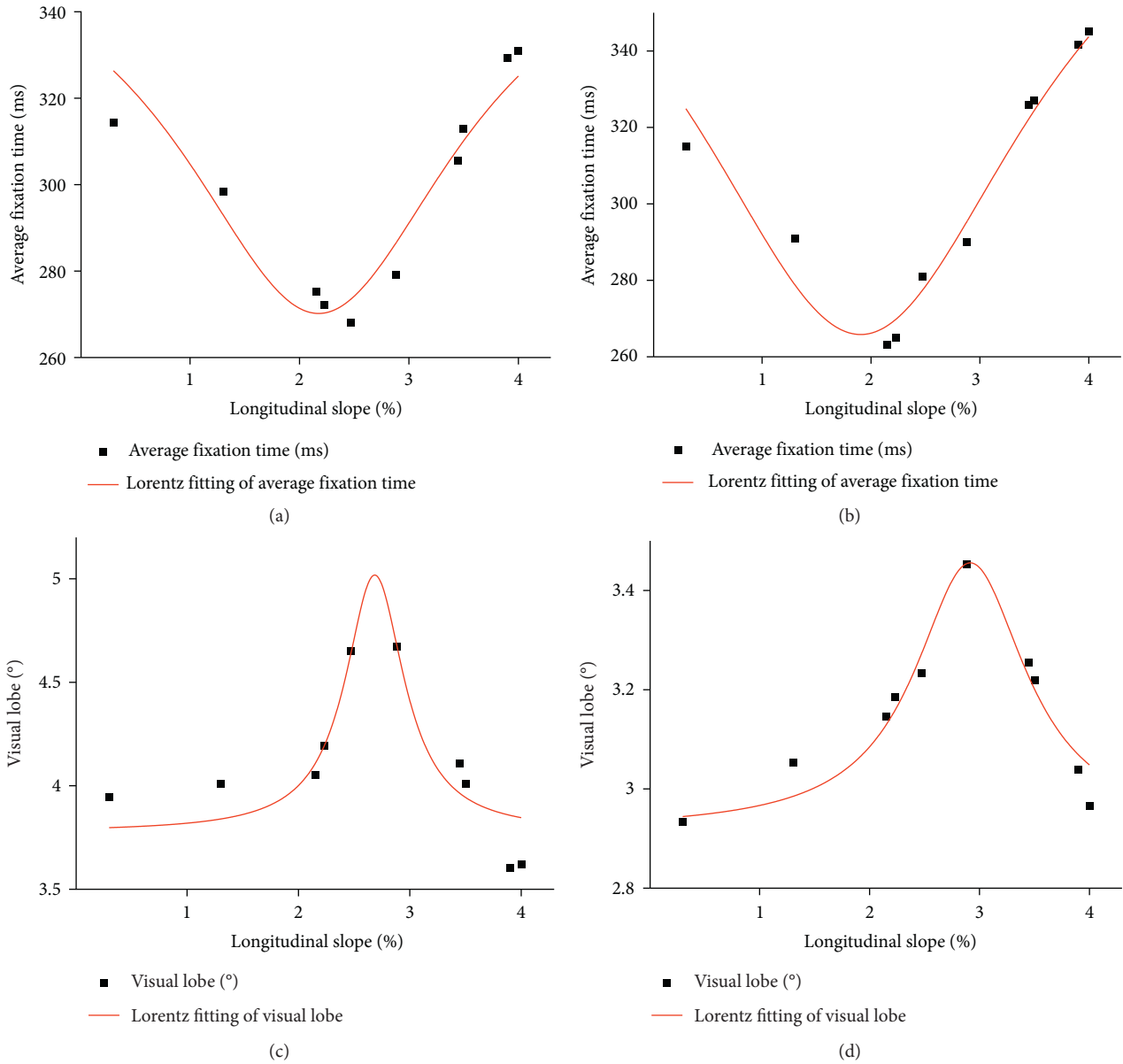
Figure 3: Curve fitting results of uphill and downhill sections. (a) The uphill average fixation time. (b) The downhill average fixation time. (c) The uphill visual lobe. (d) The downhill visual lobe.

Table 8: Fitting formula parameters and fitting model ANOVA.

Index	Up-and-down slope (direction)	Value of fitting formula parameters				Variance analysis of model		
		y_0	A	w	x_c	R^2	F	P
Average fixation time	Uphill	364.512	−457.915	3.091	2.175	0.887	3503.513	≤0.001
	Downhill	408.313	−853.622	3.814	1.905	0.936	3935.283	≤0.001
Visual lobe	Uphill	3.775	1.260	0.646	2.685	0.749	1300.865	≤0.001
	Downhill	2.916	1.049	1.237	2.916	0.889	9218.539	≤0.001

(2) In the highway tunnels, due to changes in illumination and space environment, accidents are generally concentrated at the entrance and exit of the tunnel [23, 24]. The entrance of undersea tunnel may be more dangerous due to the larger longitudinal slope.

However, the dangerous section inside the undersea tunnel is ignored. For example, the fatigue of driving in a monotonous tunnel interior environment for a long time [25] may lead to traffic accidents. Although there have been many safety improvement methods in

TABLE 9: Fitting formula parameters and fitting model ANOVA.

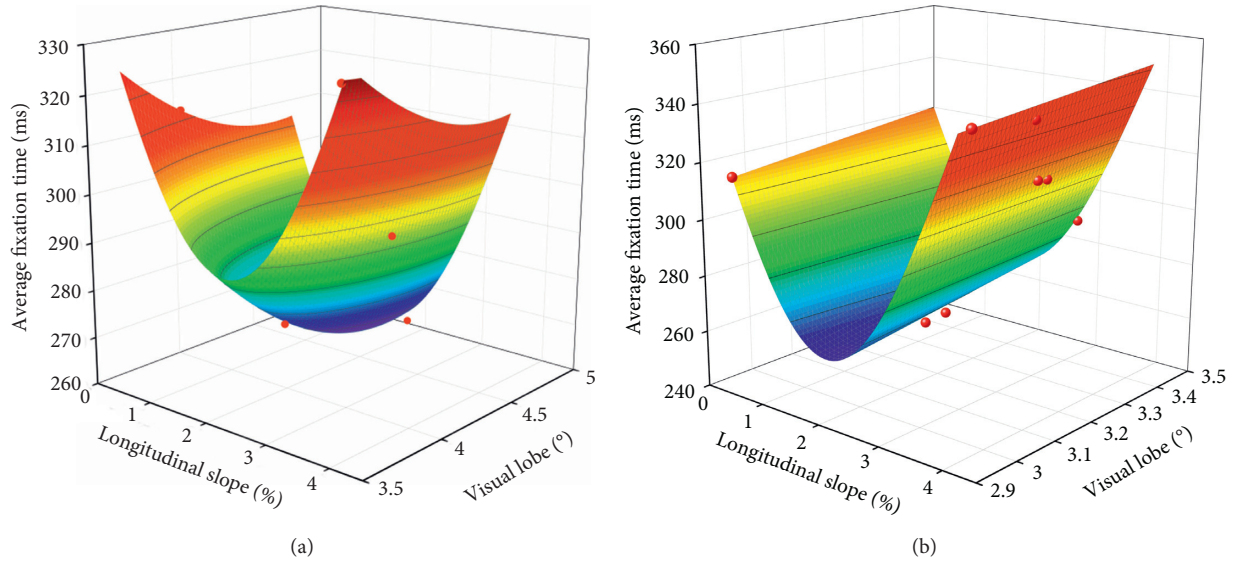| Up-and-down slope (direction)	Value of fitting formula parameters						Variance analysis of model		
	z_0	A	x_c	w_1	y_c	w_2	R^2	F	P
Uphill	1255.295	−163.315	−338.571	9.777	26.277	31.398	0.9109	2973.011	≤0.001
Downhill	−589.629	−162.251	640.472	19.156	−110.190	29.168	0.8908	1544.910	≤0.001

FIGURE 4: The variation rule of the longitudinal slope of the uphill and downhill section, average fixation time, and visual lobe. (a) Uphill. (b) downhill.

highway tunnels [26, 27], there has not been a targeted improvement study for the characteristics of long up-and-down slopes of undersea tunnels. However, the results of this study also show that the inside of the tunnel is also dangerous. For the most dangerous section in the test analysis results data of this study (about 3% of the longitudinal slope), the driver's sight should be guided by setting traffic engineering facilities (retroreflective facilities) to alleviate the driver's high load state. In particular, the tunnel entrance and exit sections should enhance the driver's sensitivity to large longitudinal slopes. For sections with a longitudinal slope value of <2%, some simple color patterns should be placed on the sidewalls of the tunnel to alleviate the driver's fatigue. These aspects would serve as future research directions.

(3) In the alignments of all subsea tunnels, the longitudinal slope was usually 0%–4%; thus, there were several points of slope change, as is the case for this test tunnel. When the driver transitioned from a large slope to a small slope, a visual transition interval occurred. In the transition interval, the driver might feel that the state of driving a vehicle is uphill or downhill and the generated slope illusion is contrary to the actual situation. Meanwhile, as the driver is in a dangerous driving state, it is imperative to propose some improvement measures for the point of slope change.

(4) In this study, the drivers' visual data collection was performed on the Jiaozhou Bay undersea tunnel in Qingdao using a real vehicle test. And there are only these few values of the longitudinal slope. No other undersea tunnel tests were carried out. However, different undersea tunnels have different alignments and space environment, which may produce different results. Thus, it is essential to conduct the same test in other undersea tunnels in subsequent studies to determine whether different tunnels had the same regularity or significant difference. In addition, the geometric design of the tunnel is comprehensive. There may have been horizontal curve when going downhill or uphill. The complicated alignments may be detrimental to the drivers [28].

5. Conclusions

(1) When a driver drove in the uphill section of the urban undersea tunnel, the average fixation time and the visual lobe were different under different longitudinal slope conditions. The average fixation time in the uphill section tended to decrease first but then increase with the longitudinal slope, whereas the visual lobe increased first and then decreased with the longitudinal slope. In the uphill section of the tunnel, the visual load was moderate at 2.47% and 2.88% of the longitudinal slope, and the driver's

visual load was the highest at 4.0% of the longitudinal slope.

(2) When a driver drove in the downhill section of the urban undersea tunnel, the average fixation time and the visual lobe were different under different longitudinal slope conditions. The average fixation time in the downhill section tended to decrease first but then increased with the longitudinal slope, whereas the visual lobe increased first and then decreased with the longitudinal slope. In the downhill section of the tunnel, the visual load was moderate at 2.15% and 2.88% of the longitudinal slope, and the driver's visual load was the highest at 4.0% of the longitudinal slope.

(3) When a driver drove in the urban undersea tunnel, the average fixation time and visual lobe under the up-and-down slope (direction) factors and the longitudinal slope (percent) factor overall were different. The interaction between the up-and-down slope (direction) factors and the longitudinal (percent) factor on the average fixation time and visual lobe were notable. The average fixation time driver under the uphill factor was smaller than the average fixation time under the downhill factor, whereas the visual lobe under the uphill factor was significantly larger than the visual lobe under the downhill factor. Furthermore, the visual load in the uphill section was smaller than that of in the downhill section.

Data Availability

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

Ethical Approval

This study was conducted in full compliance with the laws. The tests were approved by the relevant local authorities. Collecting eye tracking data were approved by participants.

Disclosure

All data in this study were for scientific research only, not for commercial use.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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