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Research Article

Variations in Naturalistic Driving Behavior and Visual Perception at the Entrances of Short, Medium, and Long Tunnels

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Driver behavior and visual perception are very important factors in the management of traffic accident risk at tunnel entrances. This study was undertaken to analyze the differences in driving behavior and visual perception at the entrances of three types of tunnels, namely, short, medium-length, and long tunnels, under naturalistic driving conditions. Using three driving behavior indicators (speed, deceleration, and position) and two visual perception indicators (fixation and saccade), the driving performance of twenty drivers at six tunnels (two tunnels per condition) was comparatively analyzed. The results revealed that the speed maintained by the drivers prior to deceleration with braking under the short-tunnel condition was significantly larger than that under the medium- and long-tunnel conditions and that the drivers had a greater average and maximum deceleration rates under the short-tunnel condition. A similar general variation of driver visual perception appeared under the respective tunnel conditions, with the number of fixations gradually increasing and the maximum saccade amplitude gradually decreasing as the drivers approached the tunnel portal. However, the variation occurred approximately 60 m earlier under the short-tunnel condition than under the medium- and long-tunnel conditions. Interactive correlations between driving behavior and visual perception under the three conditions were established. The commencement of active deceleration was significantly associated (with correlation factors of 0.80, 0.77, and 0.79 under short-, medium-, and long-tunnel conditions, respectively) with the point at which the driver saccade amplitude fell below 10 degrees for more than 3 s. The results of this study add to the sum of knowledge of differential driver performance at the entrances of tunnels of different lengths.

1. Introduction

Tunnel safety is an important traffic safety problem of freeway, as the severity of accidents in tunnels in terms of injuries, fatalities, and traffic jams is worse than that on open roads [1, 2]. A number of tunnel traffic safety investigations have emphasized that the riskiest tunnel section is the tunnel entrance, at which the accident rate is significantly higher than inside the tunnel [3–5]. This possibly relates to the fact that rear-end crashes, which have been found to account for at least two-thirds of the total accidents in tunnel sections, tend to occur at tunnel entrances [6, 7]. Such rear-end crashes can be attributed to large speed fluctuations and other risky behavior at tunnel entrances arising from the need to adjust driving behavior to adapt to the environmental transition from open road to semi-closed tunnel. The complexity of the safety problems arising at the tunnel entrance and the importance of improving traffic safety indicate the necessity for further in-depth studies on the safety of tunnel entrances.

The identification of the design elements that contribute to crashes is an essential basis for improving tunnel entrance safety. Elements analyzed in previous studies can be classified into four categories, including geometric characteristics and lighting, pavement, and traffic conditions. Geometric characteristics that have been shown to induce crashes at tunnel entrances include sharp vertical [8] and uncoordinated horizontal curvatures [2] and large longitudinal gradient [9]. Lighting conditions have also been shown to directly impact the occurrence of crashes at tunnel entrances, and crash rates have been reduced by creating smoother transitions of lighting intensity at entrances [10]. The results of a recent driving simulator study suggest that combining lighting with tunnel wall coloring could enhance the traffic safety at tunnel entrances [11]. The condition of the pavement has also been shown to be an important contributor to tunnel entrance traffic safety, with the risk of crashing increasing as the result of differences in the dry-wet condition of pavements before and after the tunnel entrance under snow- or ice-covered conditions [12]. Moreover, traffic conditions such as traffic volume and density, the composition of traffic flow, and traffic direction have been found to significantly affect crash rates at tunnel entrances [13, 14]. To sort out the sequential relations among these design elements, assessment models such as random effects negative binomial, uncorrelated random parameters negative binomial, and correlated random parameters negative binomial models have been established [15–17].

Although such models have found clear correlations between design elements and tunnel entrance crashes, the correlations have been too macroscopic to guide the specific optimization of design. To understand the fine-grained impacts of design elements on tunnel entrance crashes, researchers have attempted to analyze driving behaviors. Drivers generally reduce their speed and pay particular attention to the relative position of their vehicle and tunnel structure when driving toward a tunnel entrance [2, 18]. Typically used indicators of driving behavior include speed, deceleration (or acceleration), and position. For example, the standard deviation of speed has been found to be positively correlated with crash rates, with differences in speed between positional zones corresponding to differences in zonal crash rates. Increasing the mean and maximum deceleration increases the tunnel entrance crash rate, while the vehicle lateral position has been shown to be a reliable indicator of risk of lateral crashing [2, 6, 13, 19]. A number of derivative variables, such as time to collision [20, 21], sight distance [5], and driving workload [1, 22, 23], have also been used to elucidate relevant tunnel entrance safety problems.

Studies such as those described above have emphasized the optimization of design elements to improve driving behavior. Environmental transition has also been identified as a source of traffic safety risk at tunnel entrances. It is well understood that drivers obtain information on environmental transitions through visual perception, and previous studies looked at variation in drivers' visual perception caused by the environment transition at tunnel entrances based on eye movement indicators such as fixation, saccade, blinking, and pupil size. For example, the average duration and number of fixations have been found to significantly increase prior to entering a tunnel portal and to slightly decrease after exiting the portal [24, 25]. Similarly, saccade amplitude gradually reduces prior to entrance and then increases upon entering a tunnel portal [26], while eye blinking frequency decreases after entering a tunnel portal [27]. Upon passing through a portal, drivers' pupil sizes increase rapidly to adapt to the sharp illumination change in the environment (the so-called black hole effect) [28, 29].

Although the effects of driving behavior and drivers' visual perception on traffic safety of tunnel entrance have been widely studied, still some issues of safety of tunnel entrance have not been explained because the literature of driving behavior and visual perception has rarely considered the effects of tunnel types. The most interest one is that the crash rates at the tunnel entrance statistically vary in tunnels with different lengths, which was reported in a review by Bassan [30]. Tunnel length, which is defined as "the distance from the entrance portal of the tunnel to the exit portal of the tunnel", is closely related to topographic conditions. So the tunnel length can reflect the intrinsic characteristics of the environmental transition at the tunnel entrance in the extent. In view of the effects of driving behavior and visual perception on traffic safety, we could naturally assume that the difference of crash rates at the tunnel entrance in tunnels with different length types may be due to differences in driving behavior and visual perception.

The aims of this study were to investigate the differences of driving behavior and visual perception of tunnel entrance among tunnels with different lengths. To address these research aims, we sought to answer the following research questions:

RQ1: What are the differences of driving behavior at tunnel entrance among tunnels with different lengths?

RQ2: What are the differences of visual perception at tunnel entrance among tunnels with different lengths?

In line with this, a naturalistic driving study was conducted to obtain driving behavior and visual perception factors using a speed detector, driving videos, and eye movement-detecting glasses. Indicator data were extracted from twenty drivers under three tunnel length conditions and used to conduct a comparative analysis. The driving tests were conducted at the No. G55 mountainous freeway in Guangdong Province, China.

2. Methods

2.1. Tunnels Used in Driving Experiments. To obtain a sufficient number of tunnel samples of varying lengths, naturalistic driving experiments were carried out on a mountain freeway with a high proportion of tunnels located in the western area of Guangdong Province, China. A road section between the Huaijinan and Sihui interchanges, which has a 100 km/h design speed and three lanes per direction, was chosen as the test road for the study. The test road has a total length of 160 km in both directions and contains 30 tunnels.

To avoid interference from other design elements, six tunnels with similar entrance design elements, including alignment, pavement, and lighting conditions and portal structure, were eventually selected for analysis from among the thirty tunnels on the test course. To reduce the influence of traffic conditions, it was necessary to ensure, to the greatest extent possible, a free-flow traffic condition on the test road. Accordingly, the period from 7 : 00 to 11 : 00 am, which has a time headway in excess of 6 s, was chosen for testing.

As shown in Table 1, the selected tunnels were divided into three groups according to their respective length conditions. The tunnel length classification criteria were determined in accordance with previous studies [7, 30], with "short," "medium," and "long" used to denote tunnels with lengths of less than 500 m, from 500 to 1000 m, and from 1000 to 3000 m, respectively. Each tunnel length condition was fulfilled by two tunnels; Figure 1 shows the relative locations of the selected tunnels along the test road.

2.2. Experimental Variables and Recording Apparatus. The driving experiments were carried out in a naturalistic driving environment (the freeway), enabling us to collect valid data on driving behavior and visual perception variables as a result of the naturalistic performance of the drivers under the test conditions. High-precision, real-time, portable recording equipment, including eye tracking glasses, a video recorder, an on-board diagnostics (OBD) sensor, and a smartphone (see Figure 2), were used to capture driving behavior and visual perceptions. Obtaining real-time vehicle status information from a controller area network has been a common data collection approach in recent naturalistic driving studies.

Visual perception data were collected using eye tracking glasses (ETG-2.6; SensoMotoric Instruments GmbH Warthestrasse, Teltow, Germany) to record eye motion variables such as fixation, saccading, and blinking. Except for eye movements, real-time videos of the roadway were also recorded at the same time. The eye movement sampling frequency and driving scenario image frame rates were both 60 Hz. The imaging resolution of the videos of the roadway was 960×720 pixels, with horizontal and vertical tracking visual angles of 80 and 60°, respectively. The resolution of the eye tracking glasses was below 0.1°. The visual perceptions results were obtained and quantified using the compatible Begaze 5.0 analysis software.

Three types of driving behavior data were recorded by the video recorder, OBD sensor, and smartphone: speed (km/h) at the entrance of a tunnel, deceleration at the entrance of a tunnel (to indicate, in particular, when braking deceleration was initiated), and position (the relative real-time distance between the position of the vehicle and the tunnel entrance). Both the speed and deceleration data were sampled at 2 Hz; data were sent from the OBD to the smartphone through a Bluetooth connection. The position was calculated by interpolation following the time synchronization of the video and OBD parameters.

2.3. Participants. The test drivers were recruited through a print advertising campaign targeted at the Campus Community of the South China University of Technology and various test road engineering management companies. Additional invitations were sent through online advertising and surface mail. Ultimately, twenty drivers were chosen as participants following a trial in which the eye tracking glasses were worn by each prospective driver.

In selecting the participants, we attempted to reduce the effects of gender, age, and driving experience, the participants comprised 16 men (80%) and four women (20%), and the ratio of men to women drivers is similar to that of previous studies [7, 10]. The participants' age ranged from 26 to 40 years ($M = 32.7$ and $SD = 3.2$), reflecting the overall age distribution of drivers in China. The drivers had held their driving license for between two and twelve years ($M = 6.5$ and $SD = 3.5$), with an accumulated freeway mileage per year of between 2,100 and 12,000 km ($M = 5{,}800$ and $SD = 3{,}250$). None of the participants had driving experience on the test road and were therefore unfamiliar with the test environment. All participants had held a grade C1 Chinese driving license for at least one year and could therefore legally drive a passenger car with fewer than seven seats on a freeway. Written consent was obtained from all participants and, in all other respects, relevant ethical guidelines were adhered to.

2.4. Procedure. Each participant was subjected to a pretest phase comprising experimental instruction and adaptation to driving while wearing the eye tracking glasses. The experimental instructions included descriptions of the experimental purpose, an equipment function introduction, instruction in equipment use, and emergency safety guidelines. All participants were then required to complete and pass a quiz to verify that they satisfactorily understood the experimental instructions. Upon passing the quiz, each driver undertook a driving adaptation process before entering the formal experiment. During the adaptation task, each participant was allowed to drive freely on the test freeway for at least 10 min until they confirmed that they could drive in a normal style while wearing the eye tracking glasses. During this phase, no measurements were taken.

Following the pretesting procedures, the data collection equipment was calibrated online. ETG 2.6 software was used to calibrate the tracking glasses for obtaining eye movement data using the three-point calibration method. Next, the equipment for collecting driving behavior was prepared by establishing a Bluetooth connection between the OBD sensor and smartphone and installing the driving video recorder in the middle of the front window. Each device was checked to confirm that it was in a normal state of operation. The driving route and destination interchange on the test road were then introduced to the participants. Once the participants had confirmed that they understood the precise driving route, the testing began. The participants were instructed to drive in their normal driving styles. Each drove the course in a single direction for approximately 45–60 min, depending on their driving speed. In addition to the driver, a recorder was present in the car during each test to mark the time at which the vehicle passed through specific sections such as the tunnel entrances, static traffic signs, and kilometer posts.

Finally, the detailed data extracted from the eye movement and driving videos and the recorder time measurements were used to synchronize the experimental variables across a time chain, allowing the visual perception and driving behavior data acquired through the six selected tunnels to be extracted. For each tunnel, an analysis segment

Table 1: Test tunnel data.

Number	Name	Length (m)	Radius of horizontal alignment (m)	Gradient (%)
1	Ligongding Tunnel	325	3,200	2.20
2	Xi-an Tunnel	286	2,515	2.45
3	Shimen Tunnel	768	2,550	2.28
4	Fengkeng Tunnel	762	3,720	1.72
5	Nanmuling Tunnel	1,660	3,600	1.60
6	Dajuekeng Tunnel	1,442	2,900	0.50

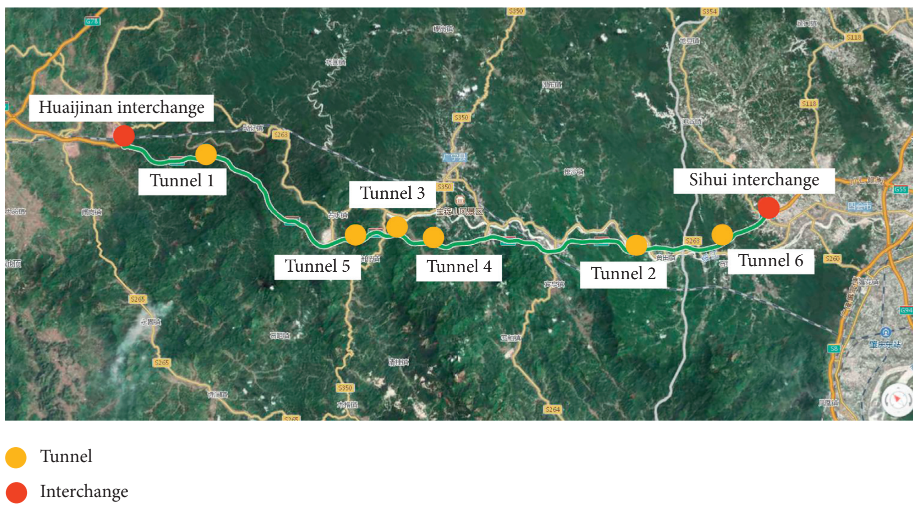


Figure 1: Selected test tunnels along the No. G55 expressway, Guangdong, China.

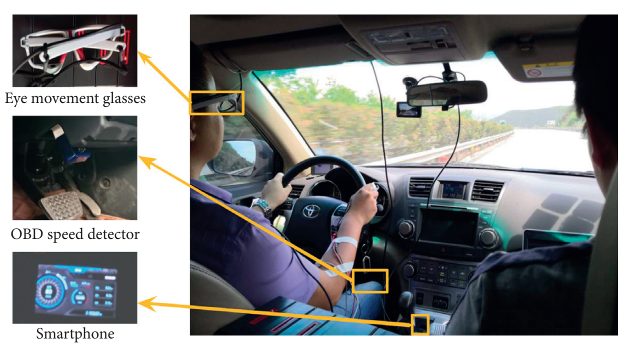


Figure 2: Vehicle and apparatus used in naturalistic driving experiments.

stretching from 1,000 m before the tunnel portal to 200 m beyond the portal was used, which allowed us to compare driving behavior and visual perception based on exact timings and longitudinal positionings on the analysis segments. For each of the three types of tunnel length, indicators of driving behavior such as speed, deceleration, and longitudinal position and indicators of visual perception such as fixation and saccade were calculated.

3. Results

To achieve the aim of getting further understanding of the variations of driving behavior and visual perception at the entrance among different tunnel conditions. 36 groups of data for the short-tunnel condition, 37 groups of data for the medium-tunnel condition, and 36 groups of data for the long-tunnel condition were used for analysis, after eliminating invalid data which were attributable to abnormal driving states and wrong equipment states.

3.1. Driving Behavior. The driving behaviors during the naturally occurring deceleration of a driver entering a tunnel entrance were analyzed. To contain the overall driver deceleration process within the range of the tunnel entrance, the entrance was defined as the road section from 1,000 m before the tunnel portal to 200 m after the tunnel portal, a longer distance than that used in previous studies [14, 30]. The analyzed indicators of driving behavior, which are listed in Table 2, include speed, deceleration rate, and vehicle position. As shown in Figure 3, the specific indicators of driving behavior were defined as follows:

V_0: speed recorded 1,000 m before the tunnel portal

V_1: speed recorded 200 m before the tunnel portal

V_2: speed recorded at the tunnel portal

V_s: speed at the beginning of deceleration by braking

V_e: speed at the end of deceleration by braking

d_{av}: average braking deceleration applied by the driver

d_{max}: maximum deceleration by braking

Site *a*: the position at which the driver begins to press their foot on the pedal (begin braking) within the tunnel entrance range

Table 2: Statistical results for driving behavior indicators.

Indicator	Units	Tunnel length condition			ANOVA result	
		Short	Medium	Long	$F(2,105)$	P value
V_0	km/h	105.3	104.9	104.7	0.033	0.967
V_1	km/h	93.4	92.6	88.4	4.402	0.015
V_2	km/h	81.6	83.2	79.6	1.963	0.146
V_s	km/h	101.5	97.1	91.6	12.652	0.000
V_e	km/h	78.1	80.7	76.0	3.746	0.027
ΔV_{0e}	km/h	27.2	24.2	28.8	2.005	0.140
ΔV_{se}	km/h	23.4	16.4	15.6	10.887	0.000
Site a	m	345	305	283	8.993	0.000
Site b	m	(−57)	(−35)	(−65)	4.984	0.009
Site c	m	125	120	84	1.472	0.234
d_{max}	m/s^2	0.85	0.75	0.65	5.207	0.007
d_{av}	m/s^2	0.38	0.31	0.26	9.311	0.000

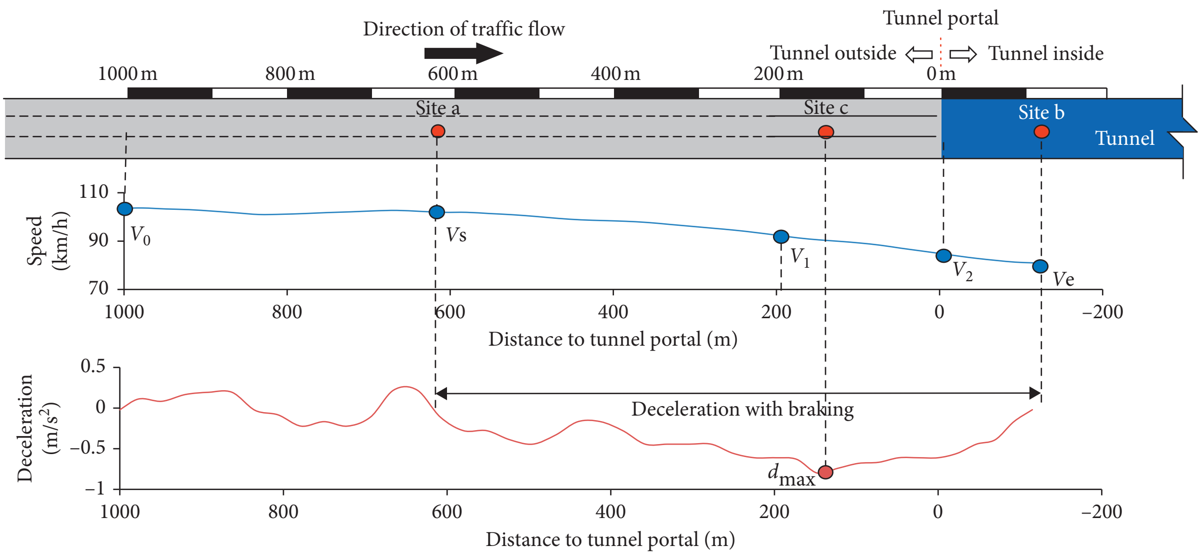


Figure 3: Examples of naturalistic driving data profiles at a tunnel entrance.

Site b: the position at which the driver finally raises their foot from the decelerator pedal (end braking) within the tunnel entrance range

Site c: the position at which the maximum deceleration with respect to the tunnel entrance is recorded

3.1.1. Speed. Analysis of vehicle speed can show if driving behavior matches the design assumptions of entrances to tunnels of various lengths, i.e., the traffic safety of a tunnel entrance can be evaluated in terms of the consistency between drivers' behavior and the real road design.

The naturalistic driving speed of each participant was measured continuously in real time and the resulting speed data were exported through the OBD interface. The average speeds at selected sites (V_0, V_1, and V_2) and at specific defined sites (V_s and V_e) are shown in Figure 4, while Table 2 contains the ANOVA results for these speed indicators. In the figure, the error bars denote the 90% confidence level and the dotted lines indicate the design speeds or speed limits imposed by China's technical regulations and safety specifications for tunnel road sections. The design speed of the test road was 100 km/h, and the speed limit in the test tunnels was 80 km/h. Because it was recorded 1,000 m before the tunnel portal and was therefore not influenced by the tunnel, V_0 could be considered the speed of the normal state of driving on the test road. As the road condition was preselected, no significant differences in V_0 were found among the three tunnel length conditions. The speed at 200 m before the tunnel portal, which Chinese safety specifications define as the beginning of the tunnel influence zone, was recorded as V_1. The expectation under the safety specifications is that a driver should start their deceleration at the beginning of the influence zone. Comparing to the average value of V_0, the average value of V_1 decreases under the short-, medium-, and long-length conditions were 11, 12, and 16%, respectively.

To assess the causes of early deceleration before entering the tunnel influence zone, we conducted an in-depth analysis of the speed at which the drivers actually began to actively decelerate. To obtain this, we measured V_s, the average speed at which the drivers began to apply pressure

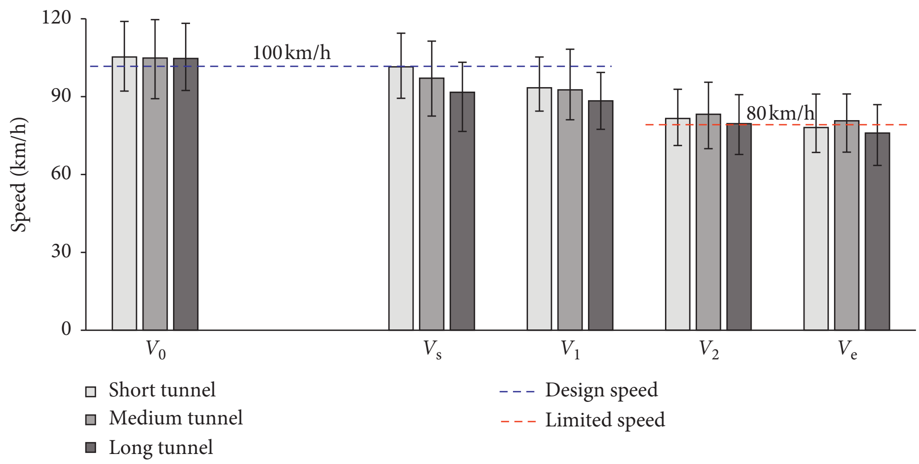


Figure 4: Drivers' speeds at tunnel entrances.

on the brake pedals within the tunnel entrance range. As the length condition changed, the drivers' brake performance varied. For short tunnels, the average value of V_s was 101.5 km/h, which was close to the average short-tunnel value of V_0. For medium tunnels, the average V_s was 97.1 km/h. The lowest average V_s (97.1 km/h) occurred at long tunnels and was approximately 13 km/h lower than the average long-tunnel V_0.

As seen in Table 2, the mean values of V_2 were very close to the speed limit (80 km/h), indicating that the drivers completed the procedure of adapting their speed to the limit when entering the tunnel portal. Furthermore, the values of V_2 were not significantly influenced by tunnel length, possibly as a result of the speed limitations prior to entering the tunnels. Nevertheless, V_2 could not be treated as the lowest speed of the deceleration process at the tunnel entrances, as the values of V_e were approximately 3 to 5 km/h lower than those of V_2, and the influence of tunnel length on V_e was significant.

According to the ANOVA results listed in Table 2, significant differences were found in V_1, V_s, and V_e, respectively. We can infer that tunnel length is a crucial influencing factor on the drivers' deceleration processes at tunnel entrances. To further examine this effect, we compared the speed differences between V_0 and V_e (ΔV_{0e}) and between V_s and V_e (ΔV_{se}), with the results listed in Table 2. In short tunnels, the average value of ΔV_{se} was 86% of the average ΔV_{0e}; in medium and long tunnels, the corresponding ratios were 68 and 54%, respectively.

3.1.2. Deceleration. To further assess the intrinsic differences in the deceleration process under different tunnel length conditions, we conducted an in-depth analysis of driving behavior based on the deceleration rate.

First, we analyzed the average value of deceleration (d_{av}), which represents the average deceleration from the beginning to the end of active braking deceleration, under the three length conditions. Table 2 lists the average values of d_{av} and the relevant ANOVA results under the three conditions. The ANOVA results confirm that tunnel length might significantly affect d_{av} ($P < 0.001$). Specifically, the average values of d_{av} were 0.38, 0.31, and 0.26 m/s^2 under short-, medium-, and long-tunnel conditions, respectively.

The ANOVA results for maximum deceleration (d_{max}) listed in Table 2 reveal that this indicator also varied by tunnel length condition at a statistically significant level ($P = 0.007$). The ordering of the d_{max} results by tunnel length followed that of d_{av}, with the largest average values occurring under the short-tunnel condition, followed in turn by the medium- and long-tunnel conditions. It is worth noting, however, that the average value of d_{max} in all cases was much higher than 0.5 m/s^2, exceeding the specified upper limit value by 70, 50, and 30%, respectively, under the short-, medium-, and long-tunnel conditions.

To determine the mechanism underlying this exceedance of safe maximum deceleration rates, we conducted an analysis of the distribution of the deceleration characteristics. Figure 5 shows the cumulative frequency curves of the deceleration rate during the active deceleration process under all three conditions. It is apparent that the inflection points of the cumulative frequency curves vary, corresponding to the 97.2th, 93.5th, and 90.6th percentiles of the long-, medium-, and short-tunnel curves, respectively. Figure 5 shows that the deceleration values corresponding to the inflection points of the respective deceleration cumulative frequency curves, which are all higher than 0.5 m/s^2 (approximately 0.65 m/s^2).

3.1.3. Position. To assess the effect of tunnel length on the drivers' deceleration processes, we carried out an in-depth analysis of the longitudinal positions at which the drivers actually began and ended deceleration with braking (sites *a* and *b*, respectively) and their positions of maximum deceleration (site *c*). Table 2 lists the average longitudinal positions of the respective sites under the three tunnel length conditions (a negative sign denotes a position inside the tunnel).

Figure 6 shows the longitudinal position (indicated by triangles) at which each driver initially applied pressure to their deceleration pedal (site *a*). The white bars sort the

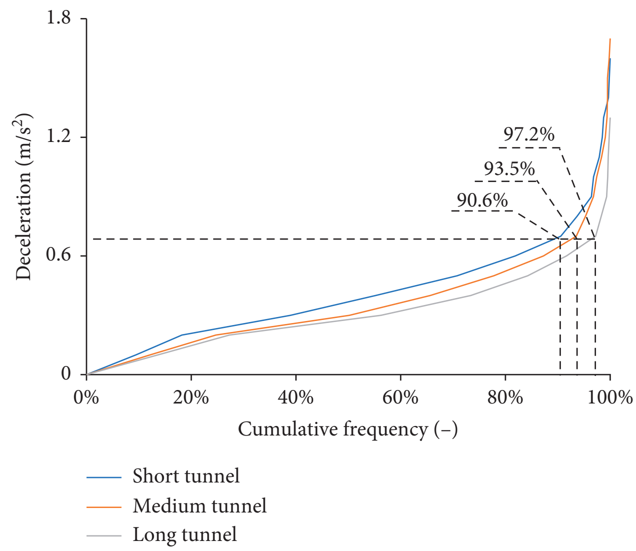
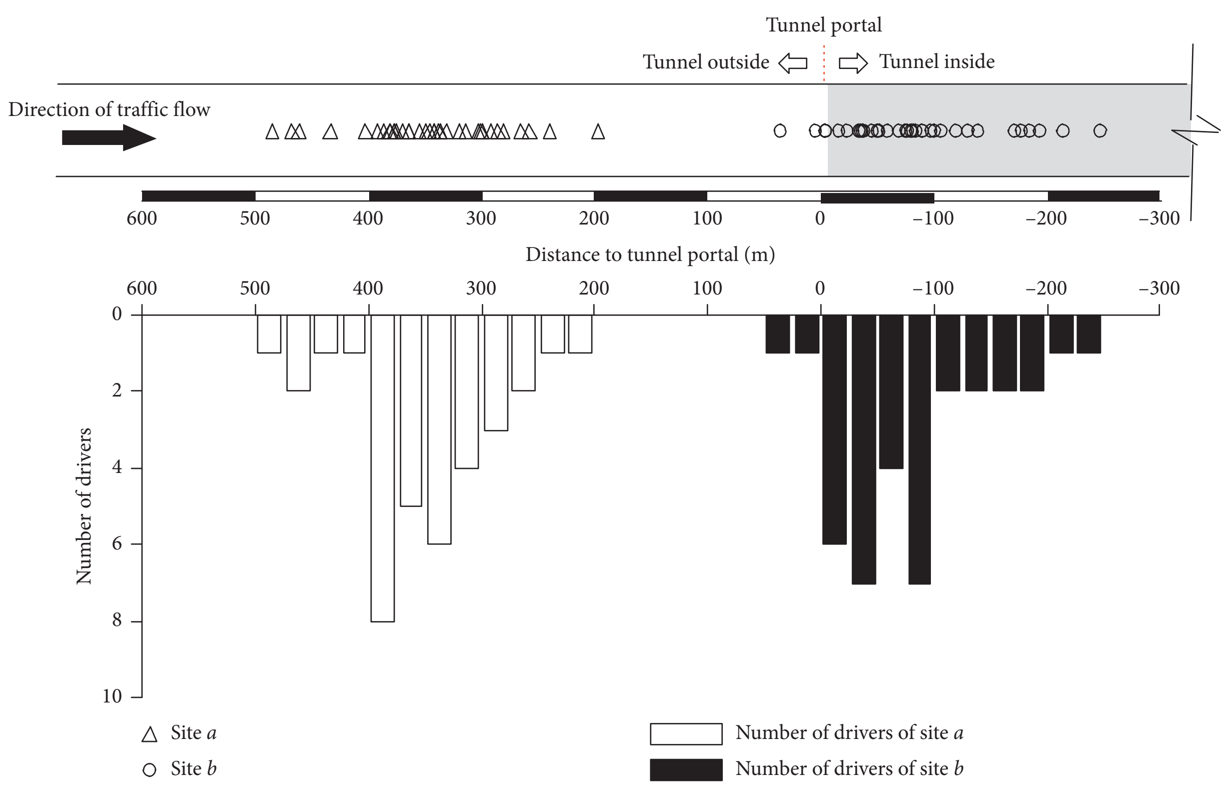
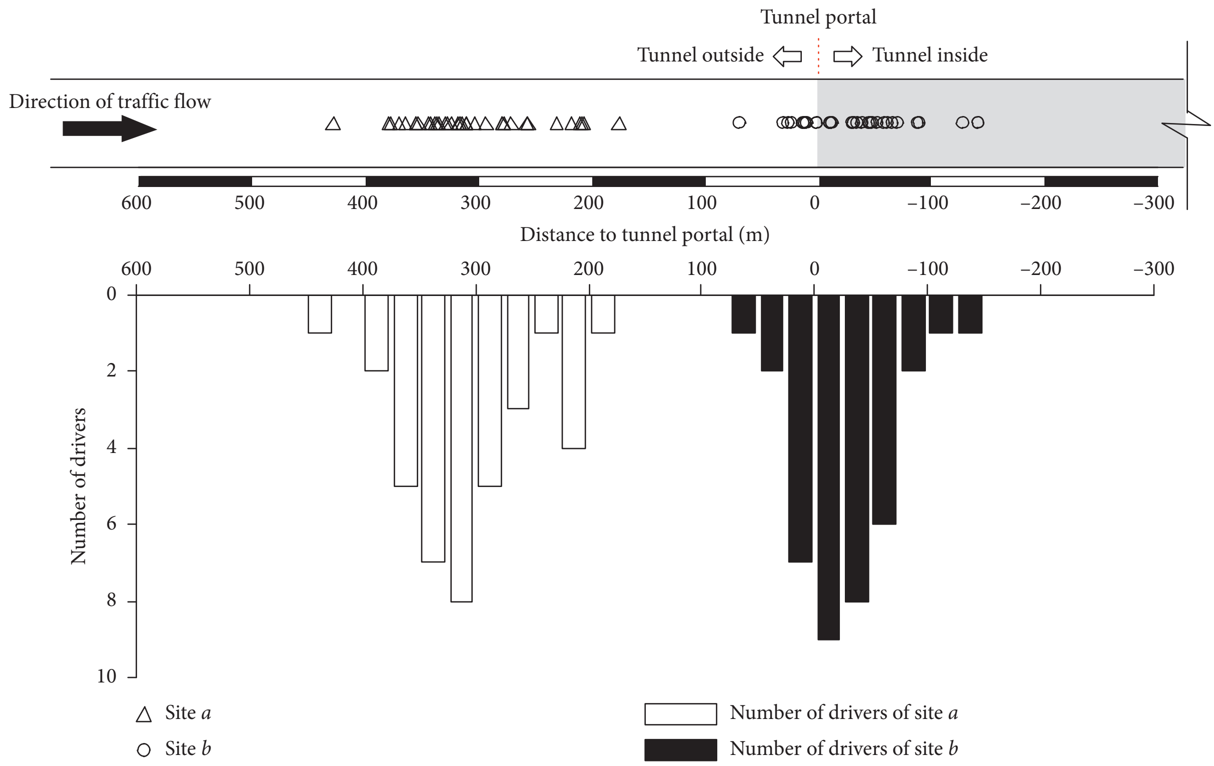


FIGURE 5: Cumulative frequency curves of deceleration rate under three tunnel length conditions.



(a)

FIGURE 6: Continued.



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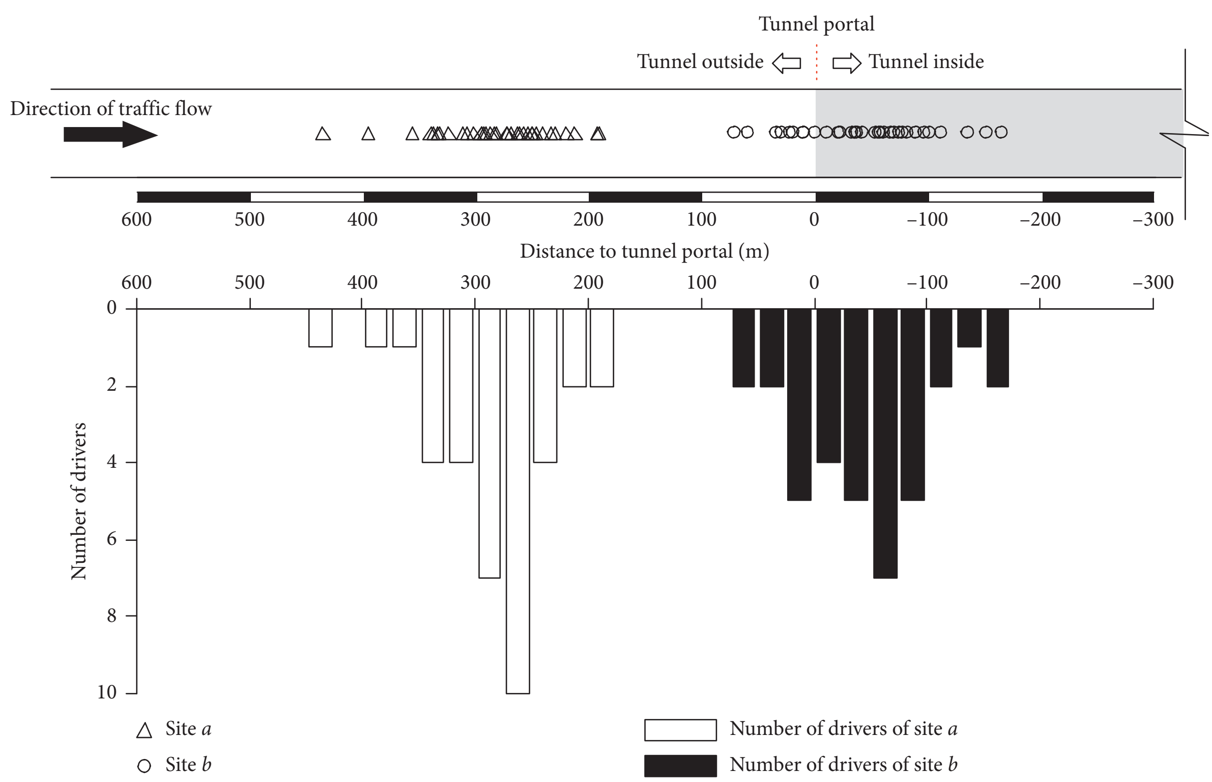


(c)

Figure 6: Localization of drivers' deceleration positions. (a) Short-tunnel condition, (b) medium-tunnel condition, and (c) long-tunnel condition.

number of drivers applying brakes at specific longitudinal positions into 25 m bins. Table 2 lists the ANOVA results for site *a*, which demonstrate that the position at which drivers began to decelerate with braking was significantly influenced by tunnel length ($P < 0.001$), with the position at which a driver initiated braking receding from the portal as the tunnel length decreased. The average site *a* values are 345, 305, and 283 m under short-, medium-, and long-tunnel conditions, respectively. The significant difference of nearly 60 m between the positions at which braking commenced under short- and long-tunnel conditions is probably attributable to the fact that the difference in speed between the point at which braking commenced and the point at the tunnel entrance (V_s–V_2) was larger under the short-tunnel condition than under the long-tunnel condition. However, this differential arises primarily from the difference between the average values of V_s, which was much higher under the short-tunnel condition, while the average values of V_2 were similar.

Figure 6 also shows the longitudinal positions at which the drivers finally released pressure on their deceleration pedals (site *b*). These are plotted as circles, with the number of drivers within each 25 m bin of position plotted as dark bars. From Table 2, we see the significant influence of tunnel length on the position of site *b* ($P = 0.009$). Looking more closely at the variation in the location of site *b* among the three length conditions (Figure 6), it reveals that the most significant difference is between the behavior under the short-tunnel condition and the behaviors under the medium- and long-tunnel conditions. Under the short-tunnel condition, only 6% of drivers completed their active braking deceleration before reaching the tunnel portal; under the medium- and long-tunnel conditions, the percentages rose to 28 and 25%, respectively. By contrast, the ANOVA results for site *c* revealed no significant correspondence between tunnel length and driver behavior.

3.2. Visual Perception. A driver's visual perception is a fundamental physiological response involving the sharing of dynamic driving information between the driver, road, and environment. As such, changes in visual perception can significantly impact driving behavior. In other words, the driver must make a comprehensive judgment of various pieces of driving-related information obtained from visual perception that will ultimately be reflected in a change in driving behavior. As tunnel entrances represent an environmental transition in the road at which sharp changes in driving information occur, it is necessary to undertake a detailed analysis of the characteristics of driver visual perception upon approaching and entering a tunnel.

In this study, the visual perception in which a driver maintained his/her focus of vision on a specific area for a period of time longer than 50 ms was recorded as a fixation, while a transfer between two adjacent fixations was recorded as a saccade. The area between each respective tunnel portal and the position 1 km before the portal was divided into an average of ten zones (see Figure 7), which were defined as Zone 1 to Zone 10, respectively. Several indicators of visual perception were measured, including the number of fixations, denoting the total number of fixations in a specific zone, and the maximum amplitude of saccading, denoting the largest saccade by the driver within a specific zone.

3.2.1. Fixations. The number of fixations is a characteristic indicator that can represent how frequently a driver negotiates dynamic road and environment information, with an increased number of fixations generally corresponding to a higher frequency of information collection by the driver. The fixation results listed in Table 3 indicate that, taking the tunnel portal as the benchmark cross section, the number of fixations generally increased as the distance to the portal decreased, a pattern that was consistent across the three tunnel length conditions.

The ANOVA results reveal that the number of fixations was significantly influenced by tunnel length only in Zone 5 ($P = 0.04$), with no significant influence found in the other zones. A closer examination of the data in Table 3, however, shows a sharp rise in the number of fixations in Zone 5 under the short-tunnel condition, which may be the source of the divergence for this zone.

Following previous studies, we divided fixations into two categories: road-ahead and road-around fixations. As seen in Figure 8, a fixation was defined as road-ahead when its pixel position fell into the image boundary between the road surface and tunnel portal; otherwise, it was classified as a road-around fixation.

Figure 9 shows the positional distribution of fixation events. Under all three tunnel length conditions, the positional distribution of fixations transformed from a scattered to a sheet distribution as the drivers drew nearer to the tunnel portal, with the percentage of road-ahead fixations increasing from 40% (Zone 10) to 75% (Zone 1). In addition, high-percentage changes in fixation type were discovered in Zone 5 (22%) under the short-tunnel condition and in Zone 4 under the medium- and long-tunnel conditions (21 and 19%, respectively).

3.2.2. Saccades. Saccading corresponds to the process in which a driver transitions between two adjacent fixations. Saccade amplitude can be used to characterize the angle of fixation transformation to provide a quantitative indicator describing the variation in the positional distribution of fixation. Using the drivers' maximum saccade amplitudes as an analytical indicator, a comparative analysis of the maximum amplitudes in each zone under the three tunnel length conditions was carried out.

Figure 10 shows the distributions of maximum saccade amplitude under the respective conditions; Table 4 lists the mean values of maximum saccade amplitude in each zone. Under all three conditions, the maximum saccade amplitude decreased upon approaching the tunnel portal. This result quantitatively explains the variation seen in the fixation positional distribution: the maximum saccade amplitude inevitably narrowed when the driver maintained their attention on the road ahead, resulting in a sheet distribution of the fixation positions.

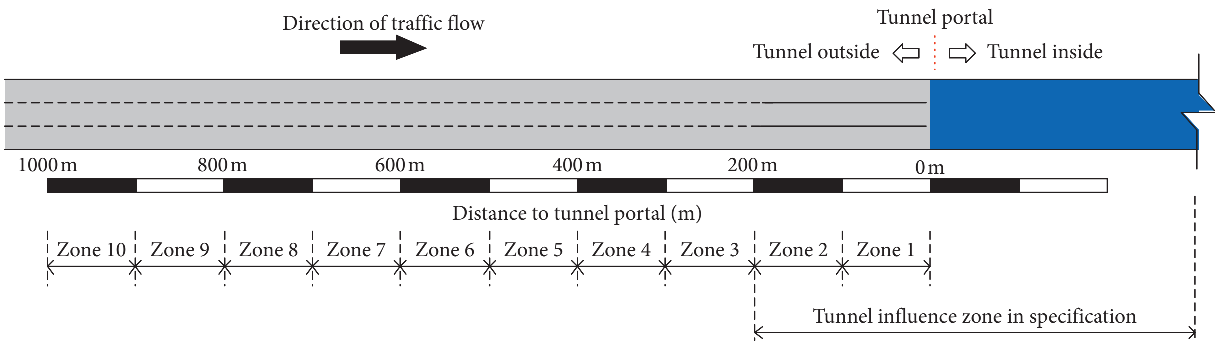


Figure 7: Division of zones before the tunnel portal.

Table 3: Statistical results for the number of fixations.

Number of fixations	Tunnel length condition			ANOVA result	
	Short	Medium	Long	$F(2,105)$	P value
Zone 10	5.9	5.4	4.9	0.705	0.496
Zone 9	7.0	7.3	7.4	0.128	0.880
Zone 8	7.3	7.8	6.1	1.929	0.150
Zone 7	7.9	6.8	6.6	1.307	0.275
Zone 6	7.2	7.9	6.9	0.615	0.542
Zone 5	10.1	7.9	8.5	3.317	0.040
Zone 4	7.5	7.5	8.0	0.172	0.842
Zone 3	7.9	8.4	8.9	0.552	0.577
Zone 2	8.7	9.1	8.6	0.398	0.673
Zone 1	11.7	11.3	11.8	0.326	0.723

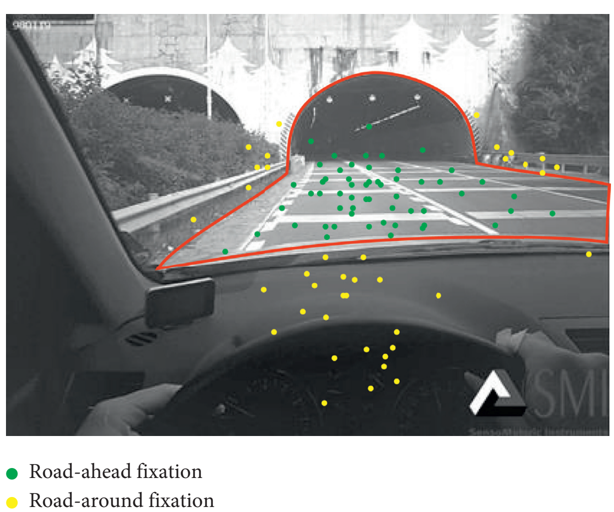


Figure 8: Division of fixation categories.

As the data in Table 4 reveal, there were significant differences in maximum saccade amplitude among five of the zones, namely, Zones 2 to 5 and Zone 9. Furthermore, Zone 5, where the divergence of behavior begins, is the only zone in which the difference in the number of fixations by tunnel type is statistically significant.

3.3. Analysis of Correlation between Driving Behavior and Visual Perception. As mentioned above, the data in Table 2 show that some of the indicators of driving behavior, including V_s, ΔV_{se}, d_{max}, and site a, were significantly affected by tunnel length. We can infer that the significant differences among these indicators by tunnel condition were related to differences in V_s: because the short-tunnel condition had the largest V_s, its ΔV_{se}, d_{max}, and site a results were also the largest. Similarly, the data in Tables 3 and 4 show that Zone 5 was the location at which tunnel length had the most significant effect on the number of fixations and the maximum saccade amplitude: the mean values of both visual perception indicators under the short-tunnel condition differed significantly from those under the medium- and long-tunnel conditions. These two patterns truly reflected how driving behavior and visual perception correlate.

According to the results listed in Table 4, the mean amplitude of maximum saccade fell below 10 degrees in Zone 5 under the short-tunnel condition and in Zone 4 under the medium- and long-tunnel conditions. Comparing these results to those for site a naturally suggests that there might be a hidden relationship between maximum saccade amplitude and the longitudinal positioning of site a. To explore this further, we defined the indicator site d as the site at which a driver's saccade amplitude first dropped below 10 degrees for more than 3 s. Figure 11 shows the relationship between sites a and d obtained using the correlation coefficient method. Under all three conditions, the active correlation was significant, with coefficients of $r = 0.80$, 0.77, and 0.79 under the short-, medium-, and long-tunnel conditions, respectively.

4. Discussion

Returning to the research aim of investigating the differences of driving behavior and visual perception of tunnel entrance among tunnels with different lengths, we discuss our results in light of the two research questions and methodological limitations.

4.1. RQ1: What Are the Differences of Driving Behavior at Tunnel Entrance among Tunnels with Different Lengths?

4.1.1. Speed Deceleration Differences. Our data indicate that the characteristics of the speed deceleration process at the tunnel entrance vary in tunnels with different lengths, even though there is no difference in the overall speed

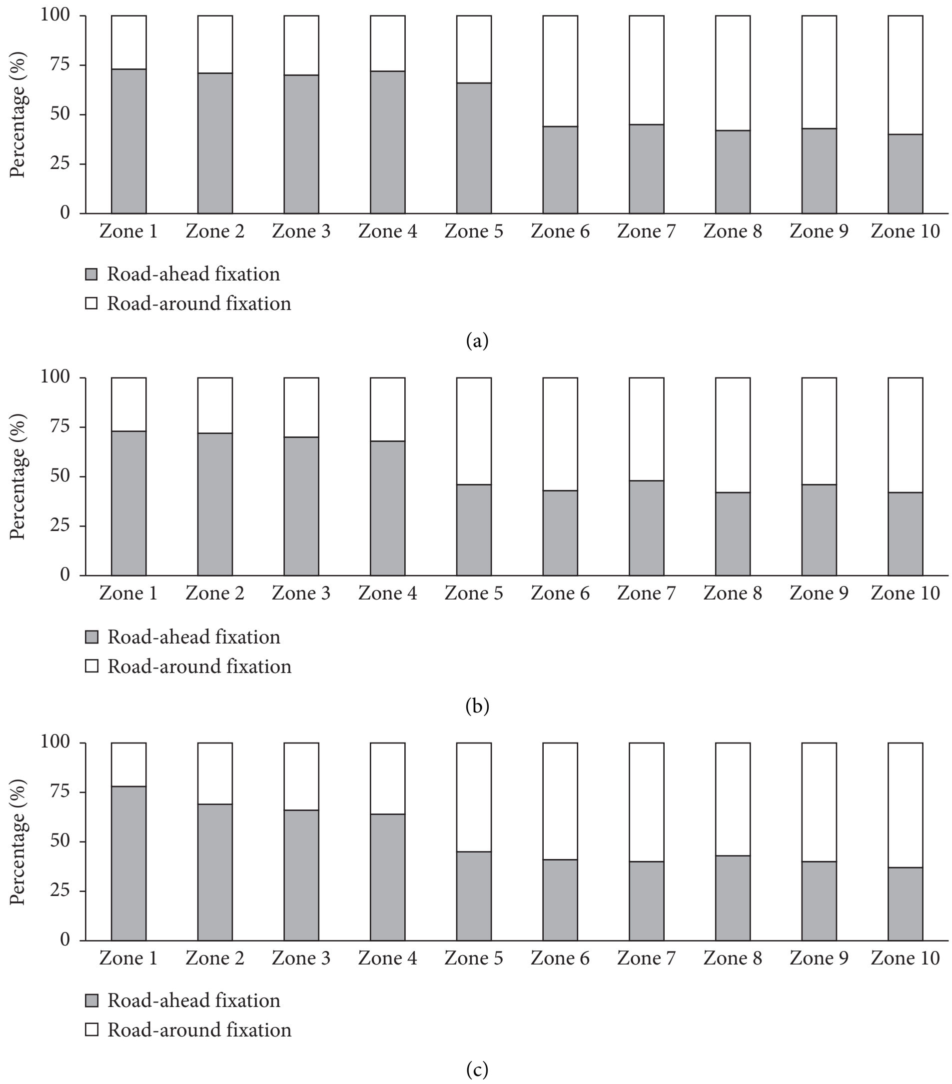


Figure 9: Distribution of drivers' fixations among different tunnel length conditions. (a) Short-tunnel condition, (b) medium-tunnel condition, and (c) long-tunnel condition.

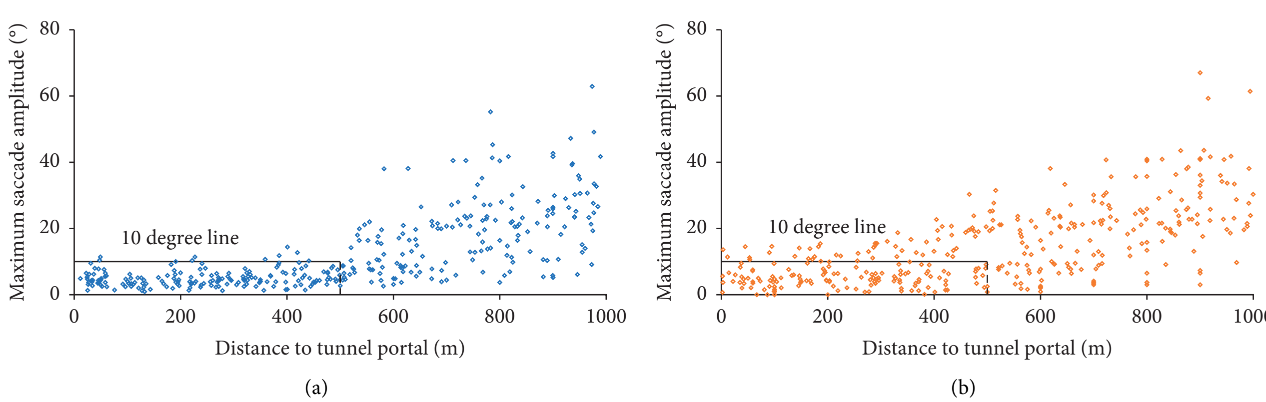
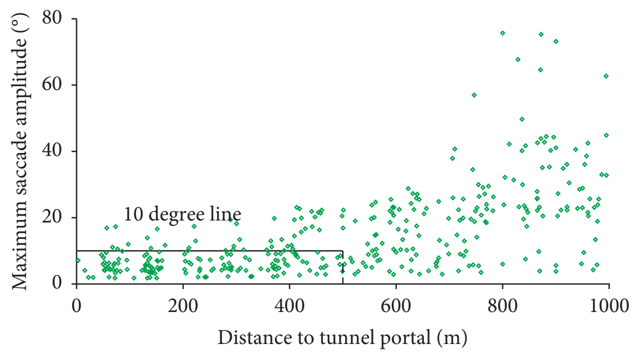


Figure 10: Continued.



(c)

Figure 10: Distribution of drivers' maximum saccade amplitude among different tunnel length conditions. (a) Short-tunnel condition, (b) medium-tunnel condition, and (c) long-tunnel condition.

Table 4: Statistical results for maximum saccade amplitude.

Maximum saccade amplitude (°)	Tunnel length condition			ANOVA result	
	Short	Medium	Long	$F(2,105)$	P value
Zone 10	27.9	30.4	27.1	0.564	0.571
Zone 9	19.5	23.9	33.4	10.672	0.000
Zone 8	23.5	20.0	21.0	1.015	0.366
Zone 7	12.7	15.2	14.6	0.838	0.435
Zone 6	11.3	13.8	13.3	1.100	0.337
Zone 5	5.8	12.5	12.1	12.980	0.000
Zone 4	5.2	7.5	7.5	3.854	0.024
Zone 3	4.7	6.8	7.0	4.270	0.016
Zone 2	4.1	6.3	5.9	4.343	0.015
Zone 1	4.9	5.9	6.6	2.032	0.136

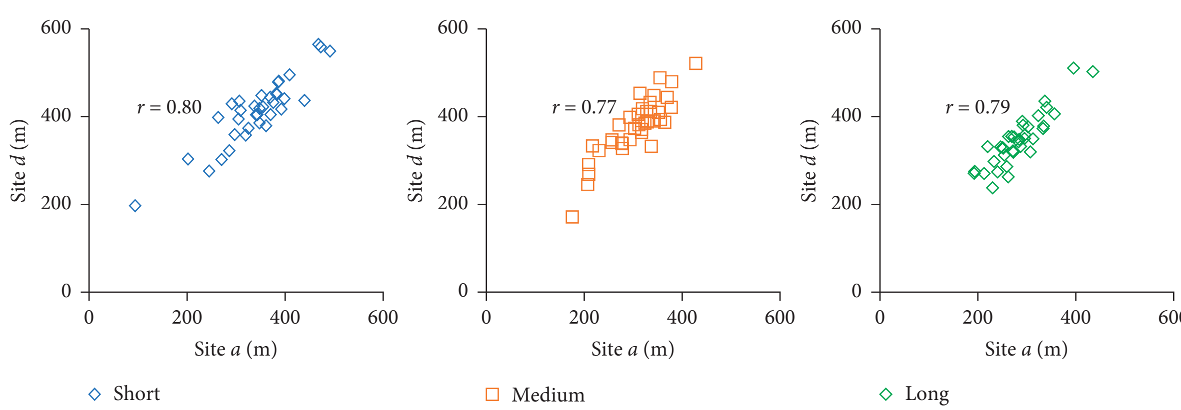


Figure 11: Correlation of sites a and d under three tunnel conditions.

deceleration amplitude. Specifically, the speed deceleration at the entrance of short tunnel showed sharper than that at the entrances of medium or long tunnels.

The results suggest that drivers tended to maintain their speed before decelerating by braking at the short-tunnel entrances but preferred to decrease their speed before decelerating by braking at the entrances of medium and long tunnels. As the overall speed deceleration amplitude under three tunnel cases was approximately the same, drivers had to decelerate with braking at the entrance of short tunnels to a greater degree than at the entrances of medium or long tunnels. Under the short-tunnel condition, the highest average and maximum decelerations occurred, which caused that drivers required larger distances to smoothly coordinate their deceleration.

In particular, the sharp speed deceleration, which is an unsafe driving behavior at tunnel entrance [6], was significantly more pronounced under the short-tunnel condition. These results might explain the statistical findings by Bassan [30] on accident rates at the entrances of tunnels of different lengths, which revealed that the accident rate in short tunnels is worse than those in medium and long tunnels.

4.1.2. Anticipatory Driving Differences. The data further suggest that drivers actually present anticipatory driving behavior under all tunnel conditions, and drivers started to decelerate before arriving at the beginning of the tunnel influence zone. But the drivers' anticipatory driving behavior at the entrances of medium or long tunnels was better than that at the entrances of short tunnel.

The anticipatory driving differences mainly presented as follows: Firstly, drivers tended to decrease their speed with no pressure on the brake pedal at the entrances of medium and long tunnels earlier than that at the entrance of short tunnel, while decreasing speed with no pressure on the brake pedal is one kind of anticipatory driving behavior [21]. Secondly, drivers who preferred to complete their active braking deceleration before reaching the tunnel portal under the medium- or long-tunnel conditions were more than those under the short-tunnel condition.

In previous research studies [12, 13], anticipatory driving was proved to be benefit for the improvement of traffic safety because anticipatory driving behavior could provide more time for drivers to prepare for upcoming speed limit changes. In fact, anticipatory driving behavior is deeply related to speed deceleration process. Under the short-tunnel condition, the least speed deceleration with no pressure on the brake pedal appeared, the highest average and maximum decelerations occurred, and the largest braking distances needed. Thus, these results also explain the statistical findings by Bassan [30] that the accident rate in short tunnels is worse than those in medium and long tunnels.

4.1.3. Implications. These results present that the differences of driving behavior at tunnel entrance among different tunnels do exist, which suggests that the tunnel length type should be considered into the traffic safety design of tunnel entrance. In addition, the value of the speed characteristic parameter in fact was different from that in design assumption of specification. For example, the parameter value corresponding to the inflection point of a cumulative frequency curve is typically used as the representative value of the design [28], and in each of these curves, the inflection is above the 85th percentile mark, a benchmark commonly used in the design process. But our data suggest that the inflection points of the cumulative frequency curves of deceleration rate under different tunnel conditions were not matched at the 85th percentile. It is well known that the consistency of design assumptions and actual situation is associated with traffic safety [9, 10]. Our finding suggests that the upper safe limit of deceleration using for the design of tunnel entrances should be stricter than that of normal road sections.

4.2. RQ2: What Are the Differences of Visual Perception at Tunnel Entrance among Tunnels with Different Lengths?

4.2.1. Difference of Fixation Number Variation. Our data suggest that, as the drivers approached a tunnel entrance, they tended to more frequently interact with the dynamic driving information obtained from the road and environment. This finding mirrors the work by Du et al. [10] who found that the closer the drivers get to the tunnel portal, the stronger the drivers desire for information.

Notably, twice fluctuations of fixation number were found under the short-tunnel condition, while the fixation number shows only a single increasing law under medium- or long-tunnel condition. This result may be explained by the established correlation between driving behavior and visual perception. Speed behavior might have affected driver visual perception in terms of how they transferred their visual attention to the road ahead. Specifically, the drivers maintained a higher speed prior to active deceleration at the short-tunnel entrance, behavior that also caused the drivers to frequently interact with road and environment before starting active deceleration. And, the drivers have decreased driving speed prior to active deceleration at the medium- and long-tunnel entrances, which may make the interaction of the dynamic driving information obtained from the road and environment become unnecessary.

4.2.2. Visual Attention Difference. Our data indicate that the drivers gradually changed their focus of visual attention to the road ahead as they approached the tunnel portal, which might explain the findings of previous studies [10, 25] that drivers prefer to obtain additional driving information to ensure safety when approaching a tunnel entrance.

The significant differences in the four continuous zones (Zones 2 to 5) indicate that approaching the entrances of tunnels with different lengths induced different saccading behavior. This finding, together with the ANOVA results, suggests that the drivers tended to narrow their visual attention to the road ahead earlier when driving into short tunnels. Similarly, we also can explain this result according to the established correlation between driving behavior and visual perception. The drivers maintained a higher speed prior to active deceleration at the short-tunnel entrances, behavior that also caused the drivers to fixate on the road-ahead area earlier (to ensure that they could manage their speed more safely) under the short-tunnel condition. Meanwhile, the effects of road-ahead fixation and maximum saccade amplitude on the onset of driver active deceleration have been indicated by our data.

Our findings are somewhat different from the work by Wang et al. [25] who found that the more visual attention the drivers paid to the road ahead, the safer status the road traffic had. Because we found that the drivers narrowed their visual attention to the road ahead earlier when driving into short tunnels; on the contrary, the safety risk in the short-tunnel condition was the highest according to the result of driving behavior. The other work by Yan et al. [24] may explain our finding, and they found "high driving tension" increases safety risk. In our results, the increases of fixation number at tunnel entrance under the short-tunnel condition may relate to the early visual attention, which could be an appearance of increasing driving tension.

4.2.3. Implications. Our results indicate that Zone 5 might be the key to determining the origin of variations in visual perception. From our results, two potential measures to enhance traffic safety at the entrances of short tunnels might be developed. First, safety measures that remind drivers to minimize their speed without braking prior to arriving at a position 500 m before the tunnel portal might be implemented. Second, safety measures to force drivers to maintain their visual attention on the road-ahead area to ensure earlier active deceleration might be devised.

4.3. Limitation. Inherent in every study are certain limitations that need to be considered when interpreting the results. Due to the experimental conditions and the main composition of our study, the findings reflect the views of tunnel length types. We cannot generalise our findings to all factors such as traffic volume, drivers' experience, and auxiliary driving condition. However, these factors are likely to have a major influence on driving behavior and visual perception [5, 14, 19].

Previous research studies [9, 11] pointed out that there are no obvious effects of road gradient on driving behavior when drivers drive passenger car (testing car) under free-flow traffic condition (testing traffic condition). But our study could not exclude the possibility that the gradient could affect driving behavior. Because deceleration variables in the short-tunnel condition were larger than that in the medium- or long-tunnel condition, while the gradient in the short-tunnel condition is higher than that in the medium- or long-tunnel condition. Thus, the effects of gradient of testing tunnels on driving behavior should be deeply analyzed in the future study based on driving tests of multigradient tunnels. Moreover, the existence of intrinsic variations in environmental transition and driving behavior at tunnel entrances remains uncertain. As the environmental factors have not been effectively quantified, the causal relationship between environmental transition and driving behavior has been insufficiently determined; that is, very few previous studies have applied specific indicators to show how environmental transition can influence driving behavior and visual perception. Furthermore, we expect to extract out quantified environmental factors from driving video by image recognition technology [31, 32], and then, we may take quantified environmental factors into analysis to deepen our understanding of the traffic safety problem of tunnel entrance.

5. Conclusion

In this study, we measured and analyzed differences in terms of driving behavior and visual perception among drivers approaching the entrances of tunnels of three different length types. Based on the data collected under naturalistic driving conditions, we found several correlations between driving behavior and visual perception. Our findings are summarized as follows.

First, we found that driving behavior at tunnel entrances, in terms of indicators such as speed, deceleration, and position, was significantly affected by tunnel length. In particular, driving behavior at the entrances of short tunnels was significantly different from that under medium- and long-tunnel conditions, which involved higher speeds prior to active deceleration (V_s) as well as higher average (d_{av}) and maximum deceleration (d_{max}). However, no significant differences could be found in terms of indicators such as V_2, V_e, or site *b*, suggesting that driving behavior might not differ by tunnel length condition once the driver has entered the tunnel portal.

Second, the distribution of visual perception results confirmed that the general variations in driver visual perception behavior were similar under different tunnel length conditions. As the drivers approached tunnel portals, the number of fixations generally increased while the maximum saccade amplitudes decreased. These variations in visual perception suggested that the drivers constantly narrowed their scope of vision and increased their visual attention to the road ahead as they approached the tunnel portal—a sign of increased driver vigilance. However, there were obvious differences in driver visual perception behavior by zone under the respective conditions. The zone in which the drivers' visual perception most sharply changed, in terms of the increased number of fixations and reduced maximum saccade amplitude, occurred earlier under the short-tunnel condition (Zone 5) than under the medium- and long-tunnel conditions (Zone 4). Moreover, in the section of road from Zones 2 to 5, the average value of the maximum saccade amplitude was significantly lower under the short-tunnel condition than that under the other two conditions.

Finally, we demonstrated an interaction correlation between driving behavior and visual perception. A driver approaching a tunnel entrance at high speed prior to active deceleration might engage in an increased number of fixations. For example, under the short-tunnel condition, the number of fixations sharply increased in Zone 5 (just before the drivers began active deceleration) because the speeds prior to active deceleration (V_s) were high. To explore this correlation further, we defined an additional indicator (site *d*, or the location at which saccading amplitude fell below 10 degrees for 3 s). The site *d* indicator was found to have a significant positive correlation with site *a* (with a location of approximately 60 m before site *a*) under all three conditions, with correlation coefficients of $r = 0.80$, 0.77, and 0.79 for short, medium, and long tunnels, respectively. This result suggests that drivers dominate their active deceleration by narrowing their visual range.

Although the findings of this study might help to explain the different traffic safety risks at the entrances of tunnels of different lengths, and our experiment results appear to be valid, we hope to expand upon this study. Traffic, road, and drive characteristics such as traffic volume, the demography and driving experience of drivers, lighting and weather conditions, and driving while fatigued should be additionally considered to strengthen our findings. Nevertheless, our findings here inform the need to apply differential safety measures in designing the approaches to tunnels of different lengths. Furthermore, the correlation we have uncovered between driving behavior and visual perception can provide guidance in effectively improving the design of safety assistance facilities at tunnel entrances.

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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