

## Research Article

# Interactive Influence Analysis of Tunnel Lateral Clearance on Driving Behavior Using Expressway Field Data

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Changes in lateral clearance are prone to drastic changes in the driving environment at the entrance and exit of the tunnel, which can cause a driver to become psychologically stressed and deviate from the center of a lane, thus creating a greater security risk. However, most of the existing regulations and studies only focus on the horizontal and vertical alignment of the tunnel entrances and exits, and there are few studies on the influence of lateral clearance on driving behavior. This study hired 15 random subjects to conduct real vehicle tests in eight tunnels on expressways with 3 design speeds by using a CAN-OBD analyzer and steering wheel angle meter. First, in five lateral clearance variation schemes, different speed characteristic indicators and steering wheel angles were selected as the indicators of driving behavior. Second, the interactive influence of the design speed, lateral clearance, operating speed, steering wheel angle, and other indicators were analyzed. Finally, paired *t*-test analysis and Wilcoxon and Friedman nonparametric tests were used to compare the differences in various indicators among different lateral clearance schemes. The results showed that when the left lateral clearance is 1.5 meters, the operating speed is increased by 3.9%, while the standard deviation of speed is small, and the driving performance is higher. When the right lateral clearance is 1.75 and 2.00 meters, the operating speed is not much different. However, the latter's speed standard deviation is smaller. By contrast, when the right lateral clearance is up to 2.25 m, the operating speed increases by 3.7%. However, the speed standard deviation also increases. Different lateral clearances have little effect on the steering wheel angle. The operating speed on the right side is higher and more stable when the design speed is 100 km/h. This study provides scientific suggestions for the setting of the lateral clearance of the tunnels.

## 1. Introduction

Highway tunnels are important structures on mountain roads, and they account for an increasing proportion of the total mileage of traveled routes. According to statistics [1], as of 2018, there were 17,738 road tunnels in China, with a total length of 17236.1 km, an increase of 1509 and 1951 km year-on-year. Among them, there were 1058 extra-long tunnels with a total length of 4706.6 km, and 4315 long tunnels with a total length of 7421.8 km. At present, the number of highway tunnels and highway mileage in China ranks first in the world [2]. The operating environment of a tunnel section has its own typical characteristics, such as complexity, diversity, and dynamics. An investigation reported [3] that

80% of the accidents in a tunnel section are caused by the violent transitions of the alignment, lighting, antiskid, and traffic safety facilities inside and outside the tunnel. Among them, the geometric design of the tunnel and adjacent roads has an important impact on driving safety. However, the Specification for Design of Highway Tunnels (JTG D70/2-2014) only stipulates that the horizontal and vertical alignment of the tunnel entrance and exit within 3 seconds of the travel range should be as consistent as possible, and there are few quantitative cross-sectional index requirements [4]. In a general case, the tunnel construction clearance is composed of the lane width, lateral width, clearance, maintained roadway, and sidewalk. When vehicles approach the entrance and exit the tunnel, the width of

the cross section inside and outside the tunnel will affect the driving psychology and driving behavior. On the one hand, lanes that are too narrow can cause sidewall effects. For example, insufficient lateral width will cause a vehicle to have a certain inward lateral offset, which is likely to reduce the parallel distance, increase the risk of vehicle collisions, and cause psychological tension or stress. On the other hand, lanes that are too wide will lead to frequent overtaking, and it is not conducive to driving safety.

As important highway features, the special linear conditions of a tunnel and their influence on driving psychology and behavior have been studied by scholars at home and abroad. Although the linear design of European national highway tunnels is based on a highway design code, it is not restricted by the design code [4, 5]. Generally, the horizontal and vertical alignment of a tunnel are determined according to the requirements of a linear highway. It is worth noting that most of the road tunnels in Switzerland and the Nordic countries are curved lines, which helps to focus the driver's attention and reduce accidents [6]. Amundsen argued that a tunnel with a large vertical gradient will make drivers feel anxious [7]. Caliendo noted that, compared with a simple straight line, a complicated horizontal curve combination will increase the possibility of accidents. Because tunnel walls can affect a driver's vision, drivers may have difficulty evaluating the curve correctly. Caliendo also established a regression model to study the relationship between tunnel length and traffic accidents and found that as the length of the tunnel increases, the frequency of traffic accidents increases [8]. As noted by Lemke, excessively long tunnels will cause drivers to lose concentration, resulting in traffic accidents [9]. According to the geometric characteristics of a tunnel, Bob Foot concluded that the acceleration and deceleration of a vehicle in a tunnel are asymmetric [10]. Leslie Edie controlled the tunnel traffic by drafting the traffic flow density of a tunnel's vertical alignment on three-dimensional coordinates and crossing it with a prefabricated density map to form a curved surface to find a safe area for traffic [11]. The United States stipulates that the minimum radius of the circular curve at the entrance and exit of a tunnel should not be less than 850–1000 m [12]. The Eurocode has no specific regulations on the alignment index near the tunnel entrance. Akihiro SHIMOJO analyzed the driving behavior of drivers near the tunnel entrances and studied how road cross section affects drivers. The results showed that 70% of drivers will become nervous when the width of the right shoulder of the road is too narrow. A wider shoulder should be set on the right side of the road to relieve the psychological pressure of the driver. The driver's perception of the longitudinal distance near the tunnel entrance is more blurred than that in the tunnel [12–14].

In the early stages of research, foreign scholars realized that the space environment in a tunnel, whether claustrophobic or spacious, may affect the psychological and physiological state of drivers. Together, these studies indicate that the alignment of the tunnel entrance and exit will cause obvious changes in a driver's eye movement characteristics, speed selection, and psychological responses [15–17]. Feng et al. [18] investigated the impact of the shoulder width of a

bridge-tunnel connection section on driving behavior and heart rate. Using HRV, Manseer et al. [19] analyzed the tension of experienced and inexperienced drivers when driving in tunnels and showed that inexperienced drivers were more nervous when driving in tunnels. In addition, other scholars [20–22] used the driving simulation cabin tests to study the relationship between the complexity of the external environment and the driver's mental workload and psychological stress and found that when driving in a more monotonous environment, the driver may feel fatigued within 20 minutes. As the driving time increases, drivers will become more fatigued and their vigilance will drop faster, especially when the driving speed increases and the lanes change. Zhang Chi et al. [23] referred to the relevant regulations of the inner and outer lateral widths of the tunnel and, based on the actual measurements, studied the speed and lateral clearance changes of vehicles at the entrance and exit of a tunnel. They also obtained the relationship between speed and lateral clearance changes and the transition section length and proposed a reasonable transition time and gradual rate of the transition section. Li [24] used a Smart Eye Pro 5.7 nonintrusive eye tracker to record the driver's eye movement parameters at different sections from the tunnel entrance and analyzed the eye movements of drivers on various road sections. Moreover, the change in vehicle speed during the whole process was recorded, and the influence range of the lateral width of the tunnel entrance and exit on the driver's vision was established, based on the analysis of the driver's eye movement data from different road sections.

Overall, there are few studies on the lateral clearance of tunnels and the transition of the entrance and exit cross sections. Most researches [25, 26] have focused on the safety of the horizontal and vertical tunnel alignment, and the mechanism of the influence of the lateral clearance on driving behavior and vehicle operation is still uncertain. However, with the continuous improvements in expressway operation management and informatization level, to avoid reducing vehicle speeds as much as possible under the premise of safety, and to maintain the sustainable and efficient operation of the tunnel sections, it is necessary to seek an effective way to address this contradiction at the technical level. This paper thus assessed the effect of lateral clearance on operating speed, to provide technical support for the safe design of lateral clearances for the entrances and exits of expressway tunnels.

The paper is organized as follows: the next sections describe the data collection and the process of preparing it for statistical analysis. Subsequently, the results are presented and discussed. The final section states the conclusions of the analysis.

## 2. Data Collection

*2.1. Test Sections.* The Letong Tunnel and Fenghuangshan Tunnel at the BinLai High-Speed Test Site were selected for field testing. The design speed of this section is 120 km/h. Moreover, three tunnels between the Boshan toll station of the BinLai Expressway and the Hezhuang toll station and the

three tunnels between the South Wutai service area of the Baomao Expressway and the Zhashui toll station were selected as supplementary scenarios for different design speed tests. The designed speed of the main line of the BinLai Expressway is 100 km/h, and the speed limit of the tunnel section is 90 km/h. The design speed of the main line of the Xikang Expressway is 80 km/h, and the speed limit in the tunnel is 70 km/h. The basic conditions of the tunnel in the experiment are given in Table 1.

Lateral clearance refers to the reserved width on both sides of the traffic lane, that is, the lateral distance from the edge of the lane to the roadside obstacles. Tunnel standards in China have made specific requirements for the cross-sectional composition and lateral width (residual width) of highway tunnels at different design speeds. The left and right lateral widths and residual width  $C$  values are independent of each other. When there is maintenance lane  $J$  or sidewalk  $R$ , the residual width  $C$  value is included in the maintenance lane or sidewalk. Otherwise, residual width  $C$  value is set separately. Generally, when the design speed exceeds 100 km/h, the residual width  $C$  value is 0.5 m. In this paper, the sum of the lateral width (left or right) and residual width  $C$  is defined as the lateral clearance. For example, the left and right lateral widths are 0.75 m and 1.25 m, respectively, at the design speed of 120 km/h; thus, the lateral clearance is 1.25 m and 1.75 m, respectively. The inner lateral clearance of the tunnel is relined in the BinLai test sites according to the tunnel standard to study the characteristics of the driver's driving behavior which is shown in Table 2.

**2.2. Test Subjects and Procedures.** In the test, 15 drivers (12 males and 3 females) aged 34 to 52 years ( $M = 44.3$ ,  $SD = 5.1$ ) were randomly hired as test subjects according to their gender, age, driving experience, and visual function. Their driving experience ranged from 10 years to nearly 30 years ( $M = 22.1$ ,  $SD = 6.4$ ). Among all the participants, 60% drove a relatively high yearly mileage (over 50,000 km) and almost all had tunnel driving experience. The test drivers were also required to have no physical defects or major accidents and hold valid driver licenses that indicate that the subjects were qualified to drive the test vehicle. The familiarities of all the subjects with the test section were counted as good, medium, or poor according to the frequency with which they traveled through the study road segments.

According to the "Highway Engineering Technical Standards" (JTG B01-2014) [27], the outline dimensions of the passenger car were selected as experimental vehicles, and the operating state data of the vehicles were tested using a CAN-OBD analyzer and steering wheel angle meter. Because there is no signal in tunnels, it is impossible to use the conventional speed measuring equipment. Through the vehicle OBD interface, CAN-OBD analyzer can analyze the original data of the internal sensors from the vehicle CAN bus. The sampling frequency of the device is 17 Hz, which can store the accumulated travel time, vehicle speed, throttle opening, and other information.

The experiments were carried out from July to September 2020 on sunny days. Before the formal experiment,

the experimenter needed to complete the experimental tunnel marking process and inform the participants of the experiment purpose, process, speed limit, etc. At the same time, the subjects needed to fill in their basic information. Prior to commencing the experiments, the experimenter installed and adjusted the CAN-OBD analyzer and steering wheel angle meter as shown in Figure 1. Meanwhile, the experimenters needed to communicate with the driver to ensure that the instruments have the least impact on the driving behavior. During the experiments, drivers should drive freely according to their own driving habits but must strictly follow the yellow markings. The experimenters marked the exact time when the subjects drove through the entrance and exit of the tunnels, so that the data could be matched and extracted later. After the experiment, the experimental data were saved in time. When the one-time experiment was completed, the test driver was changed. After all the subjects finished the tests, the tunnel was relined to start another lateral clearance experiment. In the supplementary test stage, the experimental process of the BinLai and Baomao expressways is similar to that of the BinLai test site except for the difference in design speed and speed limit. The test scene is shown in Figure 2.

### 3. Methodology

**3.1. Index Selection.** The quantitative indicators of driving behavior mainly include the behavior of drivers' perception, judgment, and manipulation. Driver's perception behavior is a process of acquiring external information such as road environment and traffic events through vision and hearing. The driver's judgment behavior is mainly reflected in the reaction time, distance, and speed estimation and attention level of the driver to the changes of road conditions. Driver's control behavior can be characterized by the operation of steering, gear, acceleration, and deceleration and other indicators. Among these indicators, the one based on vehicle running state is undoubtedly the most intuitive. Most studies analyzed driving behavior based on one or two kinematic parameters between lateral operation and speed. In general, the entrance and exit of a tunnel are affected by the transition of horizontal and vertical alignment, light and dark adaptation, driving environment, and other factors. Drivers are prone to psychological and physical changes, and the speed of the vehicle can fluctuate greatly. It is easy to decelerate at the entrance of a tunnel and become eager to drive out of the tunnel and accelerate at the exit [28]. In addition, in order to prevent the vehicle from deviating from the centerline of the road when entering and exiting the tunnel and while driving in the tunnel, the driver should adjust the steering wheel angle in real time according to changes in the driving environment and road conditions. The angular velocity of the steering wheel will reflect how smoothly the driver turns the steering wheel [29]. The frequency of the vehicle deviating from the normal trajectory will increase owing to the difference between the lateral clearances of the main line in the tunnel. This indicates that the driver's lane keeping ability and the control stability of the steering wheel have decreased. Consequently, this paper selects vehicle speed and

TABLE 1: The basic conditions of the tunnel (upward direction).

Expressway	Tunnel	Length (m)	Interval (m)	Entrance radius (m)	Exit radius (m)
BinLai high-speed test site	Fenghuangshan	803	—	2200	0
	Letong	530	960	1500	0
BinLai	Qiaolingqian	695	—	2850	0
	Letong	2010	610	4420	2850
	Magong temple	655	200	0	4420
Baomao	South Wutai	2564	—	1500	800
	Qingcha	1342	3300	800	0
	Zhongnanshan	18020	460	0	400

TABLE 2: Tunnel lateral clearance marking scheme.

Expressway	Design speed km/h	Speed limit km/h	Scheme number	Lateral clearance ( $L_C/m$ )	
				$L_{Cright}$	$L_{Cleft}$
BinLai high-speed test site	120	100	1	1.75	1.25
			2	2.00	1.50
			3	2.25	—
BinLai	100	90		1.25	1.00
Baomao	80	70		1.00	0.75



FIGURE 1: Equipment installation.

steering wheel angle as indicators of driving behavior in tunnel sections.

The CAN-OBd analyzer was used to collect real-time vehicle speed data, and the sampling frequency was 17 Hz. According to the formula of “ $s = \int v dt$ ”, the speed is calculated by accumulating an integral to obtain the corresponding driving distance, so that the driving distance has a one-to-one correspondence with the operating time point. On the basis of preliminary processing of the vehicle speed data, the speed indicators selected in this article are average speed, 15th percentile speed, 85th percentile speed, and the standard deviation of speed. Among them, the operating speed that is 85th percentile speed extracted from continuous speed data is available for further calculation based on the speed distribution. The vehicle speed standard deviation

reflects the driver’s ability to maintain speed. A small speed standard deviation indicates that the driver can maintain a stable speed with better speed maintaining capability, and vice versa.

By analyzing the characteristics of the steering wheel rotation stability when the driver passes through the tunnel and using the steering wheel angular velocity as an indicator, the steering wheel angular velocity calculation formula is as follows:

$$\omega_i = \frac{(\theta_{i+1} - \theta_{i-1})}{2\Delta t} \quad (1)$$

In (1),  $\omega_i$  is the  $i$ -th sampling angular velocity,  $\theta_i$  is the  $i$ -th sampling angle,  $\Delta t$  is the sampling interval time, and the sampling interval time is 0.6 s in the experiment.



FIGURE 2: Experimental scene: (a) entrance of tunnel, (b) inside of tunnel.

**3.2. Analysis of Variance.** This paper shows that the same sample has undergone different lateral clearance scenarios (standard form and enlarged clearance), which conforms to the relevant sample situation. Thus, we used paired  $t$ -test analysis and Wilcoxon and Friedman nonparametric test methods to compare the differences in various indicators between different lateral clearance schemes.

The paired sample  $t$ -test is mainly used to analyze the difference and contrast relationship between related quantitative data [30, 31]. If the difference between the paired samples  $x_1$  and  $x_2$  is  $d_i = (x_1 - x_2)$  and it is independent, it obeys a normal distribution. Whether the overall expectation  $\mu$  of  $d_i$  is  $\mu_0$ , the following statistics can be used:

$$t = \frac{(\bar{d} - \mu_0)}{(s_d / \sqrt{n})}. \quad (2)$$

In (2),  $i = 1, \dots, n$  and  $\bar{d} = \sum_{i=1}^n d_i / n$  is the average of the paired sample differences.  $s_d = \sqrt{\sum_{i=1}^n (d_i - \bar{d})^2 / (n - 1)}$  is the standard deviation of the paired sample difference. The null hypothesis  $H_0$  of this statistic is  $\mu = \mu_1 - \mu_2 = \mu_0$ , where  $\mu_1$  and  $\mu_2$  are the mean values of the first population and the second population, respectively.

If the paired sample  $t$ -test does not meet the prerequisites of normal distribution, the Wilcoxon rank sum test of related samples is used. This method is mainly used to test whether the populations of two related samples are significantly different, and the null hypothesis is that the distribution of the population of two related samples is not significantly different. The test principle is as follows: suppose that two samples with sample sizes  $n_1$  and  $n_2$  come from the same population distribution ( $n_1 \leq n_2$ ); on the premise that  $H_0$  is established, the overall median of the difference between the two related samples is 0; then theoretically, the sum of the positive and negative ranks of the samples should be equal, and  $T_+ = T_- = n(n + 1)/4$ . Due to sampling error, the value of statistic  $T$  is not equal to  $n(n + 1)/4$ . If  $T$  is farther from  $n(n + 1)/4$ , the corresponding  $P$  value is smaller. When  $T$  exceeds a certain threshold,  $P \leq \alpha$ ,  $H_0$  is rejected.

The Friedman test method is mainly used to test whether the overall distribution of multiple related samples (3 or more) is significantly different [32, 33]. The null hypothesis is that distribution of multiple related samples in the population is not significantly different. When the number of observations is large, the statistic of the Friedman test obeys the  $\chi^2$  distribution, and the formula of the test statistic is as follows:

$$\chi^2 = \frac{12}{bk(k+1)} \sum_{i=1}^k \left( R_i - \frac{b(k+1)}{2} \right)^2. \quad (3)$$

In (3),  $k$  represents the number of samples,  $b$  represents the number of sample observations, and  $R_i$  represents the rank sum of the  $i$ -th group of samples.

According to the associated probability value corresponding to the given  $\chi^2$  statistic, if the associated probability is less than or equal to the significance level  $\alpha$ , the null hypothesis is rejected, and the overall distribution of multiple related samples is considered to be significantly different. Otherwise, the null hypothesis is accepted, and the population distributions from multiple samples are not significantly different.

## 4. Results

### 4.1. Data Analysis

**4.1.1. Comparison of Operating Speeds under Different Lateral Clearances.** Figure 3 shows the speed change curves of different drivers between different lateral clearance schemes. Most drivers have basically the same speed change trend of first increasing and then decreasing. Few drivers exhibit obvious deceleration behavior in the tunnel entrance section. The speed limit value required by the experiment is high, which is consistent with the main line speed limit. On the other hand, the tunnel entrance section is straight, and most drivers thus did not decelerate. The speed at the exit section of the tunnel tends to decrease. The reason is that, in addition to the greater psychological load of the driver in the exit section of the tunnel, the exit section has a smaller radius

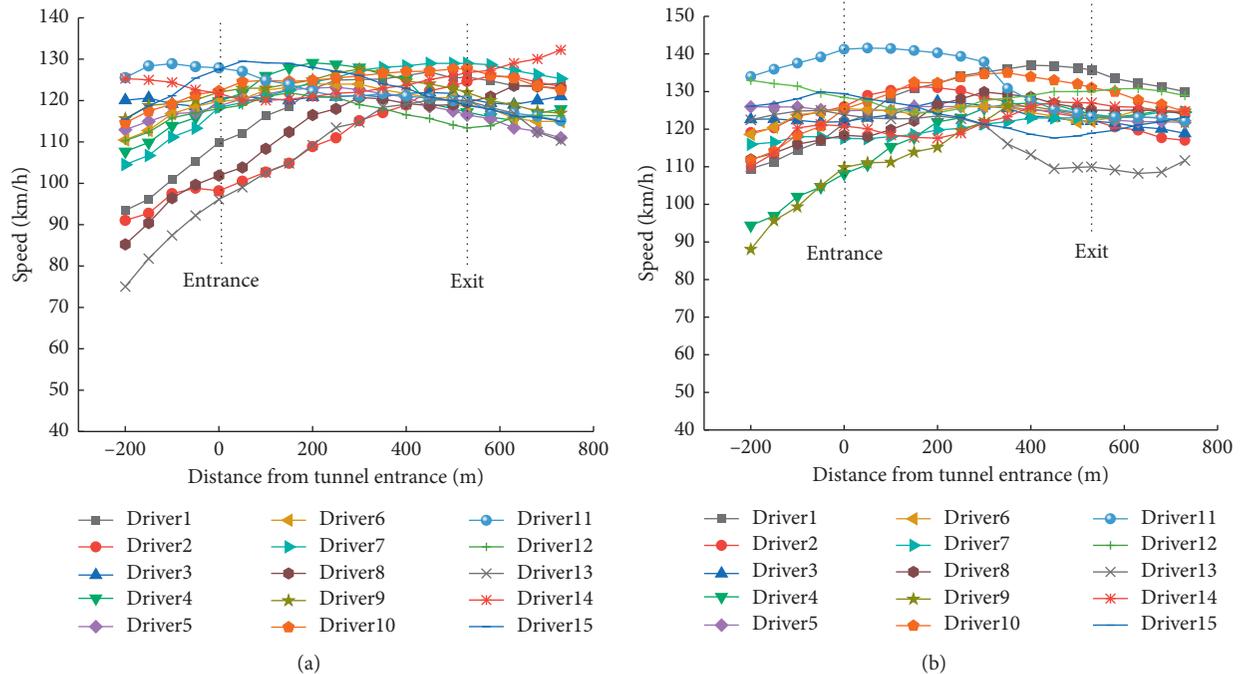


FIGURE 3: Operating speed change between different left lateral clearance schemes. (a) Scheme 1. (b) Scheme 2.

of horizontal curve radius, and the driver has to slow down due to the linearity.

According to the statistical results of different driver speeds, the average speed, 15th percentile speed, operating speed, and speed standard deviation of different schemes are obtained. The comparison of various speed indicators is shown in Figure 4. The change trends of the speed indicators of the two schemes are the same from the perspective of overall changes. The speed indicators in Scheme 2 are higher than those in Scheme 1, except for the speed standard deviation index. The average vehicle speed of Scheme 1 is maintained between 105 km/h and 125 km/h, while the average speed of Scheme 2 is maintained between 115 km/h and 130 km/h. The 85% operating speed of Scheme 2 is 4.6% higher than that of Scheme 1. The change in the speed standard deviation shows that the speed distribution of the entrance section of the tunnel is relatively discrete, the speed distribution of the middle section and the exit section of the tunnel is more concentrated, and the speed dispersion degree of the two schemes is not much different.

Figure 5 shows the driver's speed change curve between different lateral clearance schemes. As shown in Figure 5, the speed changes are not consistent when the driver is driving in the left and right lanes, and the speed of the tunnel entrance section tends to increase when the lateral clearance is on the right side. The reason is that the opposite direction was selected when measuring the influence of the lateral clearance on the right side, and the driver slowed down in the entrance section.

Figure 6 shows the variation curves of various speed indicators for different right side lateral clearances. On the whole, the operating speeds of Scheme 1 and Scheme 2 are the same as the trends of first decreasing, then increasing,

and then decreasing. In contrast, Scheme 3 shows a trend of increasing first and then decreasing. Compared with Scheme 1 and Scheme 2, the average vehicle speed and 85% operating speed of Scheme 3 are significantly higher. As a result, the lateral clearance on the right side of Scheme 3 is 2.25 m, and the driver can obtain a relatively wide lateral safety distance. The sidewall effect of the tunnel has little impact on the driver's behavior, making the operating speed of Scheme 3 higher. However, Scheme 3 has the largest vehicle speed standard deviation, Scheme 1 is the second largest, and Scheme 2 is the smallest. The speed difference between the entrance section and the middle section of the tunnel in Scheme 3 is large, which makes the vehicle speed more discrete.

#### 4.1.2. Analysis of Operating Speed at Different Design Speeds.

Different design speed tunnels are set with different speed limit values, which makes the operating speeds of vehicles in the tunnel vary. Generally, the operating speed increases as the speed limit value increases. To compare the operating speed difference of the two tunnel lateral clearance schemes at different design speeds, three tunnel scenes with different design speeds were selected: the design speed was 80 km/h (scenario 1, speed limit 70 km/h), 100 km/h (scenario 2, speed limit 90 km/h), and 120 km/h (scenario 3, speed limit 120 km/h). For these scenarios, a comparative analysis of operating speed at different design speeds is carried out. The entrance and exit alignment of the three scenarios are shown in Table 2.

Due to the different alignments of tunnel sections at different design speeds, based on the principle of controlled variables, the selected tunnel should be located on a straight

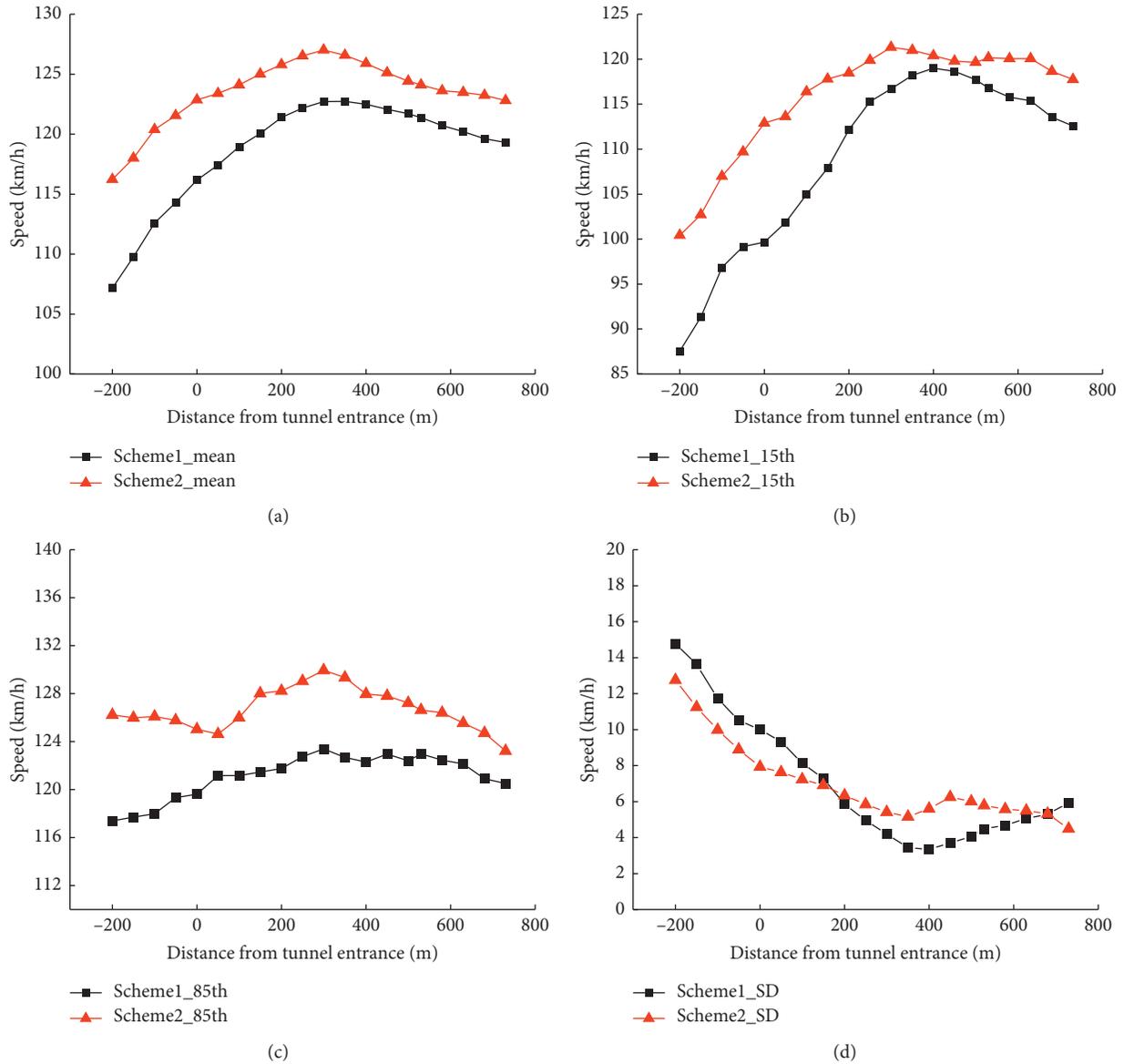


FIGURE 4: Variation of speed indicators for different left lateral clearances.

line or a curved section with a similar radius as much as possible. Considering the different lengths of the tunnels, in order to facilitate the comparative analysis of the data, 7 speed characteristic sections were selected at the same position at the entrance and exit of the tunnel (100 m inside the cave, 200 m outside the cave), and 9 speed characteristic sections were selected for the middle section of the tunnel, for a total of 16 speed characteristic point sections. Since only the left lateral clearance was tested in scenario 1, only the operating speed in the left lateral clearance was analyzed.

In the left-side lateral allowance environment, the entrance section of the tunnel is a straight section or a large radius curve section. Scenario 2 at the exit section of the tunnel is located on a straight section, while scenarios 1 and 3 are located on the curved road section, but the radius of scenario 1 is relatively small. As shown in Figure 7, the

trends of vehicle speed in the three scenarios are inconsistent. The changing trend of the speed at the entrance and exit of the tunnel in Scenario 1 is to decrease first and then increase. In scenario 2, the operating speed is relatively stable, and the operating speed is maintained between 75 km/h and 80 km/h. The vehicle speed in scenario 3 shows a trend of first increasing and then decreasing, and the vehicle speed is maintained between 107 km/h and 125 km/h. In the right lateral allowance environment, there is a large difference in the radius of the entrance and exit of the tunnel between scenarios 2 and 3, which makes the speed changes of the two scenarios inconsistent. In summary, the alignment of the road section is not the only factor that affects the speed change of the tunnel entrance and exit section. The tunnel section with the lower design speed is more sensitive to the alignment change.

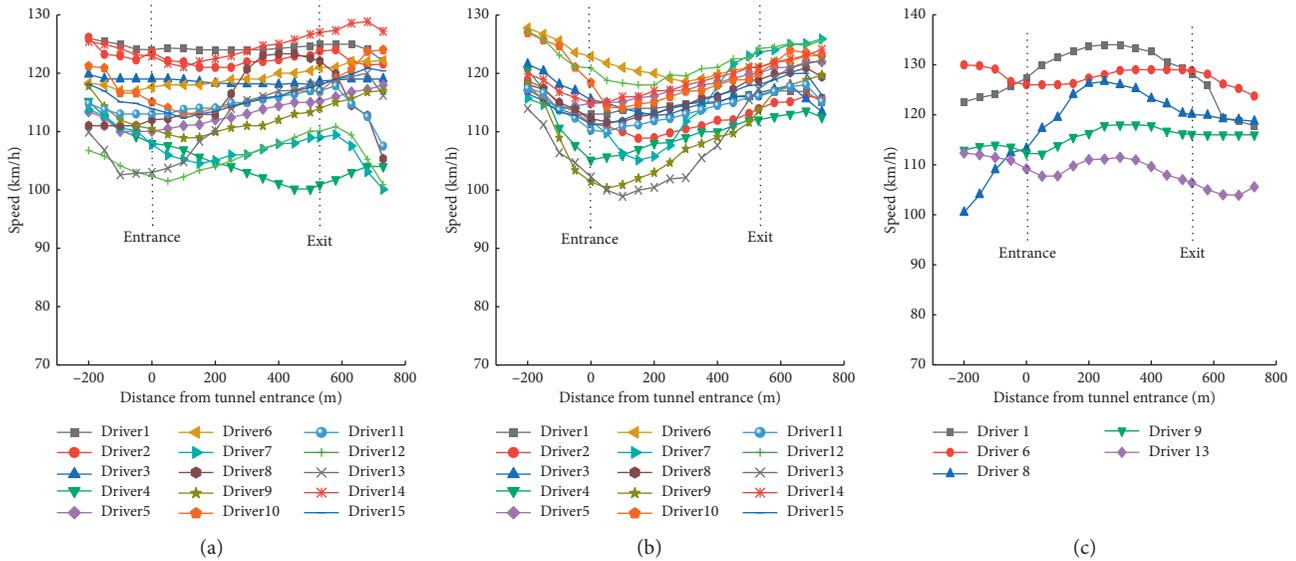


FIGURE 5: Operating speed change between different right lateral clearance schemes. (a) Scheme 1. (b) Scheme 2. (c) Scheme 3.

**4.1.3. Comparative Analysis of Steering Wheel Angular Velocity.** According to the steering wheel angle data of 15 drivers passing through the tunnel, the angular velocity was calculated. The average value of the steering wheel angle of 15 drivers is used to eliminate the influence of individual driver differences. Figure 8 provides the angular velocity of the driver's steering wheel for different left-side lateral clearances.

As shown in Figure 8(a), the steering wheel angular velocity change trends of the two schemes are not much different, and the angular velocity is maintained at  $\pm 0.4^\circ/\text{s}$ . Figure 8(b) shows that the angular velocity distribution of Scheme 2 is relatively concentrated.

The angular velocity changes of the driver's steering wheel for different schemes in the environment of the right lateral clearance are shown in Figure 9. The steering wheel angular velocity in the three schemes fluctuates around the zero point, and the fluctuation range is at  $\pm 1^\circ/\text{s}$ . It can be seen in the box plot that the angular velocity distribution of Scheme 1 is more concentrated, Scheme 2 is the second, and Scheme 3 is the most dispersed. Since the steering wheel angular velocities of the three schemes all meet the prerequisites of the single-factor analysis of variance, the single-factor analysis of variance is performed.

**4.2. Discussion.** For a clearer description of the difference in operating speed change under different tunnel lateral clearances, according to the sample size, we use the Shapiro-Wilk (SW) method to test the data for normality, and the significance level is 0.05. The normal test results are shown in Table 3.

For the left lateral clearance, the Wilcoxon nonparametric test method was used to test the significance of the speed indicators of the two schemes. The results are shown in Table 4. As seen in Table 4, except for the speed standard deviation, the  $P$  values of the other speed indicators are all

less than the significance level of 0.05, indicating that the average speed, 15th percentile speed, and operating speed of the two schemes are significantly different.

Figure 10 shows a box diagram of the speed change of different tunnel sections (entrance section, middle section, and exit section) in the left-side lateral clearance environment. For the median, the average speed, 15th percentile speed, and operating speed of Scheme 1 are 120.1 km/h, 113.1 km/h, and 121.6 km/h and for Scheme 2 are 123.9 km/h, 118.6 km/h, and 126.3 km/h. The median of each index in Option 2 is higher than that in Option 1, indicating that the increase in the lateral width of the tunnel increases the running speed. There are differences in the driving speed of the drivers between the two schemes in different tunnel sections. The mean and median of Scheme 2 are significantly higher than those of Scheme 1, and the speed distribution is relatively concentrated. The two schemes show a trend of increasing first and then decreasing overall. In summary, increasing the left-side lateral clearance of the tunnel has a significant impact on the speed of small vehicles. Compared with the standard section form (Scheme 1), adopting the scheme of increasing lateral clearance (Scheme 2) can increase the operating speed. The running speed of different tunnel sections (entrance section, middle section, and exit section) tends to increase, while the speed dispersion tends to decrease.

For the right lateral clearance, according to the test results of homogeneity of variance, the operating speeds of the three schemes do not have variance consistency with the standard deviation ( $P < 0.05$ ), so the Welch test result is regarded as the final result. Through multiple comparisons, the Tamhane result is the final result, and the results of the analysis of variance are shown in Table 5. Based on the results of the analysis of variance, there are significant differences in the operating speed and standard deviation of different tunnel lateral clearance schemes. The results of postevent multiple inspections show that there are significant differences between the operating speed and standard

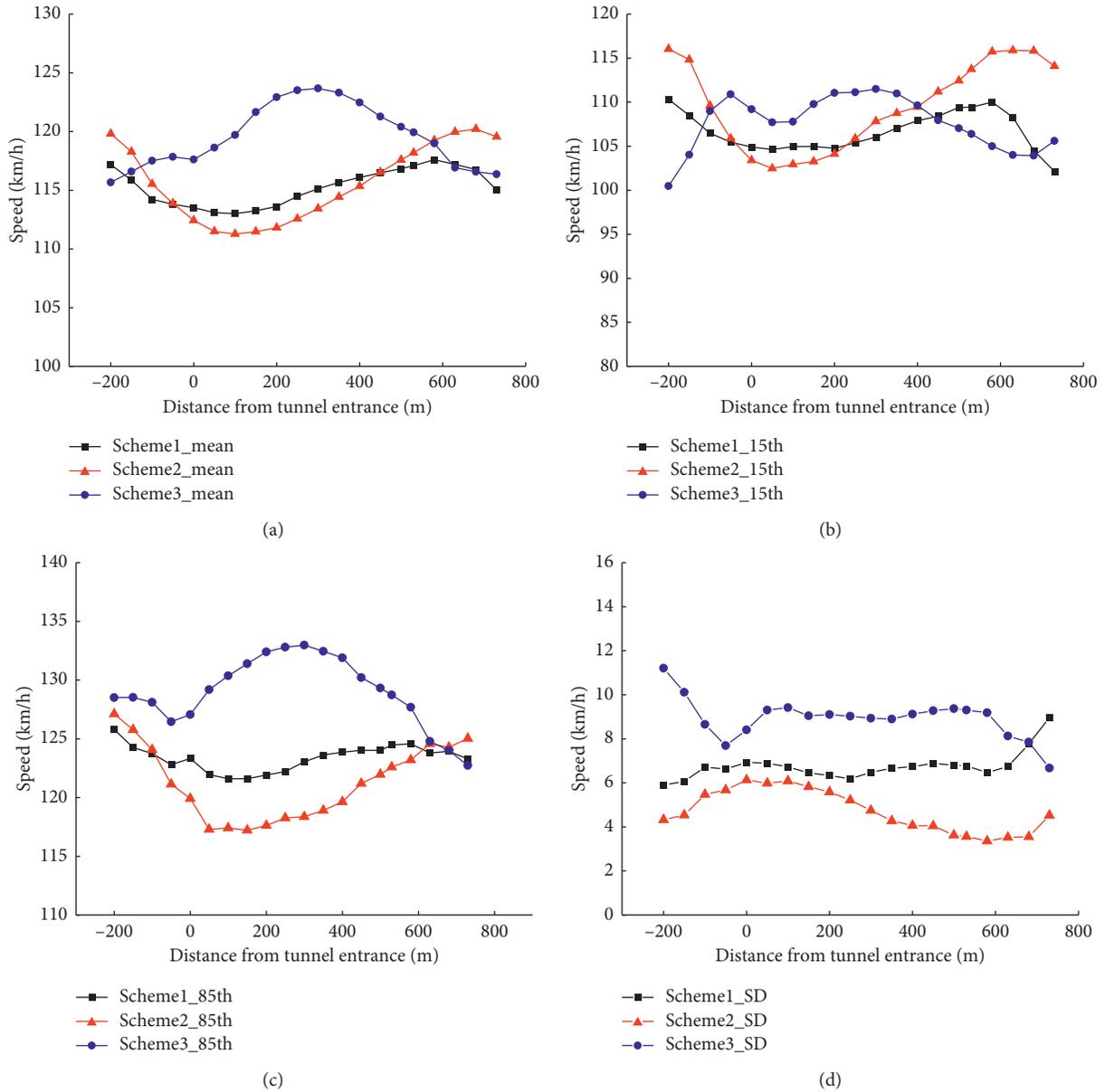


FIGURE 6: Variation of speed indicators for different right side lateral clearances.

deviation of 85% of the drivers under different tunnel lateral clearances. The mean value of operating speed and the mean value of standard deviation of Scheme 3 are significantly higher than Scheme 1 and Scheme 2, and Scheme 1 is higher than Scheme 2. This shows that when driving in the right lateral clearance environment, the use of Scheme 2 has little effect on the speed improvement of small cars, but the driver's speed control ability is better. The speed improvement of Scheme 3 is significant, but the driver's speed control ability worsens. Figure 11 shows a box diagram of vehicle speed changes in different road sections (entry section, middle section, and exit section) in the environment of lateral clearance on the right side. There are significant differences in the speeds of different tunnel sections. Scheme 3 of the entrance section and the middle section has the highest speed, while the dispersion is also the largest, and

Scheme 2 of the exit section has the highest speed. Regardless of the tunnel section, the speed dispersion of Scheme 2 is the smallest, which indicates that the driver's speed control ability designed by Scheme 2 is relatively stable. From the perspective of overall changes, Scheme 1 and Scheme 2 show a trend of first decreasing and then increasing, while the trend of Scheme 3 is increasing first and then decreasing.

The descriptive statistical analysis and single-factor results of different design speed schemes are analyzed, as shown in Table 6. It can be seen that the average operating speed of different design speed scenarios is different, the speed limit value has a significant influence on the operating speed, and the operating speed increases with the increase of the speed limit value. For the degree of speed dispersion, Scenario 1 is smaller than Scenario 2 and smaller than Scenario 3, indicating that the higher the design speed, the

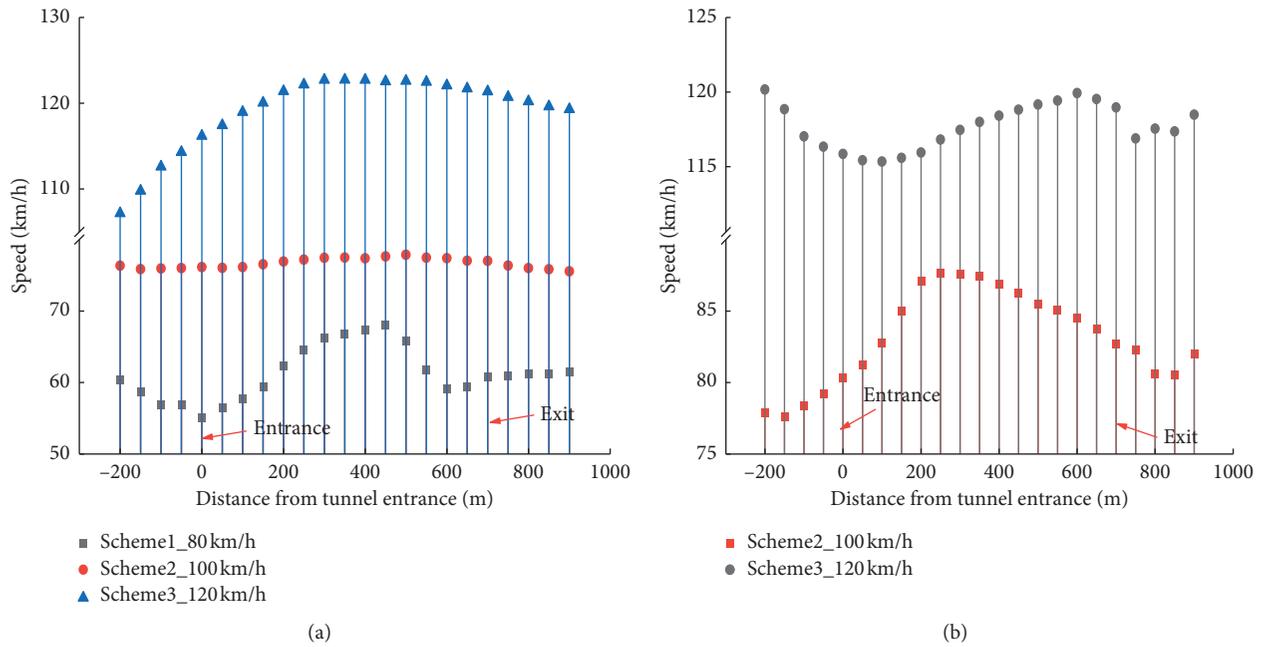


FIGURE 7: Speed changes for different design speeds. (a) Left lateral clearance. (b) Right lateral clearance.

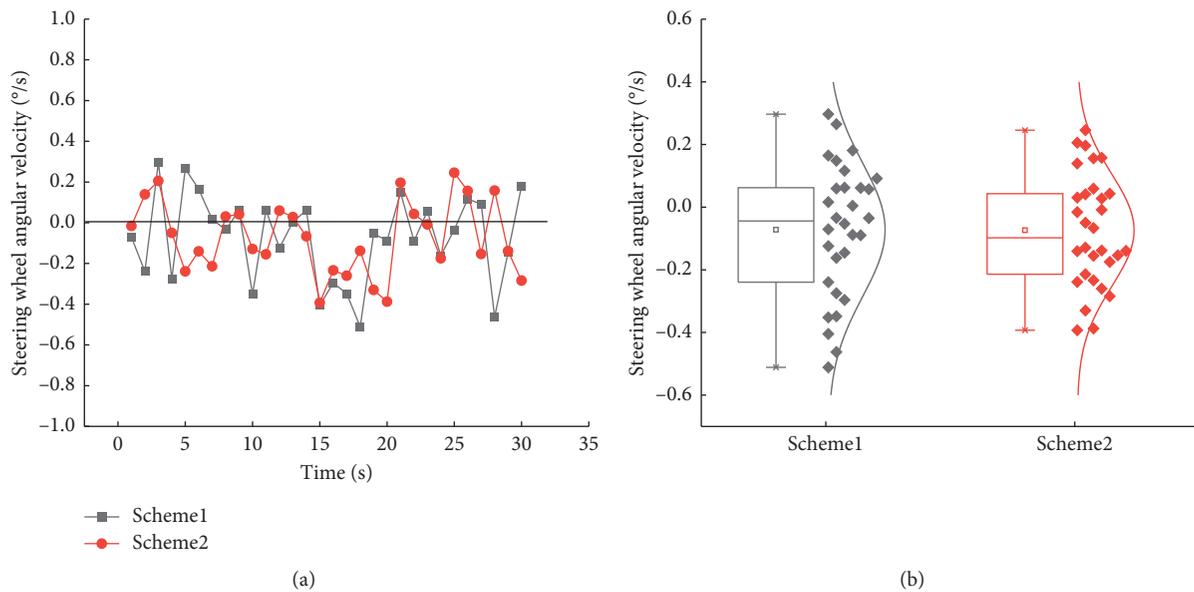


FIGURE 8: Angular velocity of driver's steering wheel for different left lateral clearances. (a) Angular velocity change of different schemes. (b) Comparison of angular velocity box plots of different schemes.

greater the degree of dispersion of the speed of the tunnel section. In Scenario 2 (design speed of 100 km/h), when the vehicle is driving on the right side at a higher speed, the speed standard deviation is smaller, which is more conducive to ensuring driving safety. In Scenario 3 (design speed of 120 km/h), the left and right lateral clearances have little effect on the driving behavior.

Through the paired *t*-test analysis of the angular velocities of the two schemes, it can be seen that, as shown in Table 7, the significant probability of angular velocity between Scheme 1 and Scheme 2 is greater than 0.05,

indicating that there is no significant difference in angular velocity between the two schemes. Increasing the lateral clearance in the left lateral clearance environment has no effect on the driver's lane keeping ability. The results of variance analysis showed that there were significant differences in the angular velocities of the steering wheels with different right lateral clearances ( $F = 3.257$ ,  $P = 0.043 < 0.05$ ).

The results of further postevent multiple inspections are shown in Table 8. The significant probability of steering wheel angular velocity between Scheme 1 and Scheme 3 is

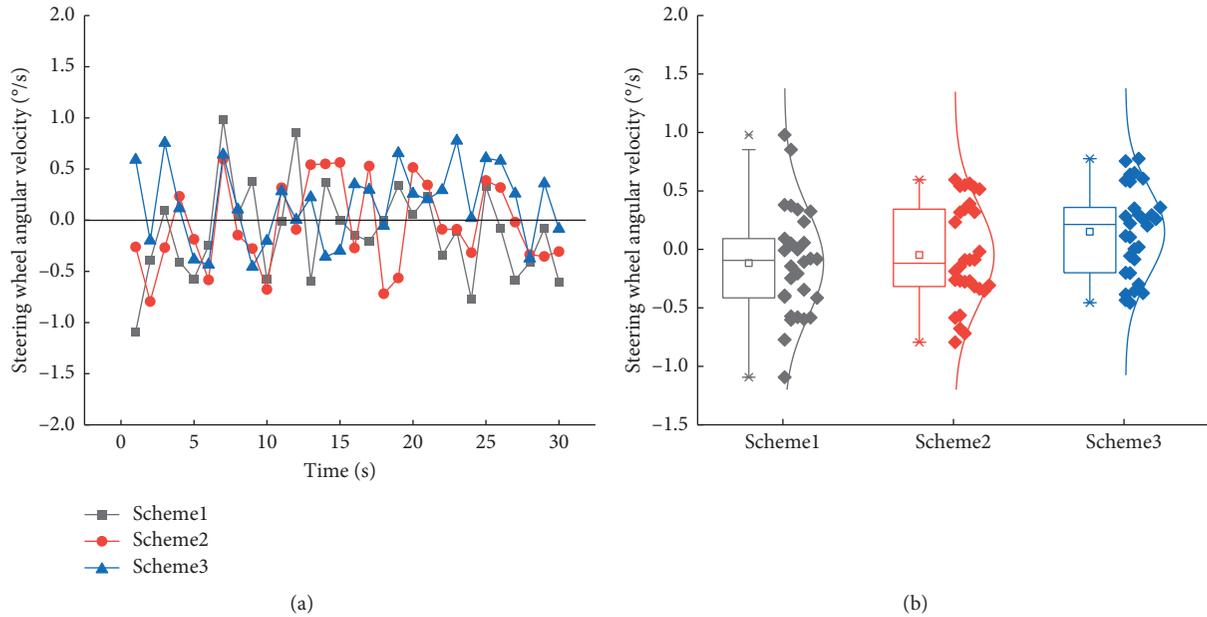


FIGURE 9: Angular velocity of driver’s steering wheel for different right lateral clearances. (a) Angular velocity change of different schemes. (b) Comparison of angular velocity box plots of different schemes.

TABLE 3: SW normal test result.

	Scheme number	Index	Statistics	<i>P</i>
Left	Scheme 1	Average speed	0.825	0.002*
		15th percentile speed	0.866	0.010*
		Operating speed	0.886	0.023*
		Standard deviation	0.873	0.013*
	Scheme 2	Average speed	0.895	0.033*
		15th percentile speed	0.780	0.000*
		Standard deviation	0.840	0.004*
Right	Scheme 1	Operating speed	0.948	0.335
		Standard deviation	0.942	0.315
	Scheme 2	Operating speed	0.932	0.169
		Standard deviation	0.911	0.066
	Scheme 3	Operating speed	0.949	0.359
		Standard deviation	0.922	0.110

\*indicates significant difference.

TABLE 4: Wilcoxon nonparametric test results.

Index	<i>Z</i>	<i>P</i>
Average speed	-3.920	0.000*
15th percentile speed	-3.920	0.000*
Operating speed	-3.920	0.000*
Standard deviation	-0.075	0.940

less than 0.05, indicating that there is a significant difference in steering wheel angular velocity between the two schemes. Overall, the angular velocity of the steering wheel tends to decrease when the right lateral clearance is increased from 1.0 m to 1.75 m, indicating that the driver’s lane keeping ability has improved.

Based on the above analysis, the degree of dispersion of steering wheel angular velocity in different tunnel lateral clearances is different, and increasing the tunnel lateral clearance tends to improve the driver’s steering wheel angular velocity dispersion. From the results of the analysis of variance, however, there is no difference in the lane keeping

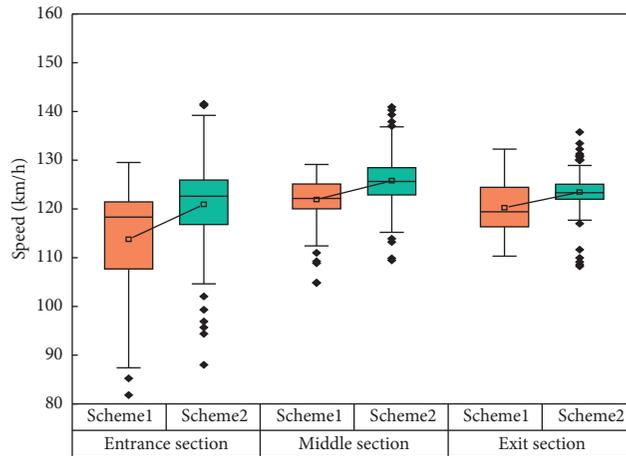


FIGURE 10: Speed changes in different tunnel sections for different left lateral clearance.

TABLE 5: Analysis of variance and multiple test results afterwards.

Dependent variable	Number (I)	Number (J)	Mean difference (I-J)	Standard deviation	Obvious	Statistic	Obvious
Operating speed	Scheme 1	Scheme 2	2.115	0.750	0.028*	37.479	0.000*
		Scheme 3	-5.588	0.701	0.000*		
	Scheme 2	Scheme 3	-7.703	0.970	0.000*		
Standard deviation	Scheme 1	Scheme 2	2.048	0.259	0.000*	98.363	0.000*
		Scheme 3	-2.179	0.253	0.000*		
	Scheme 2	Scheme 3	-1.227	0.299	0.000*		

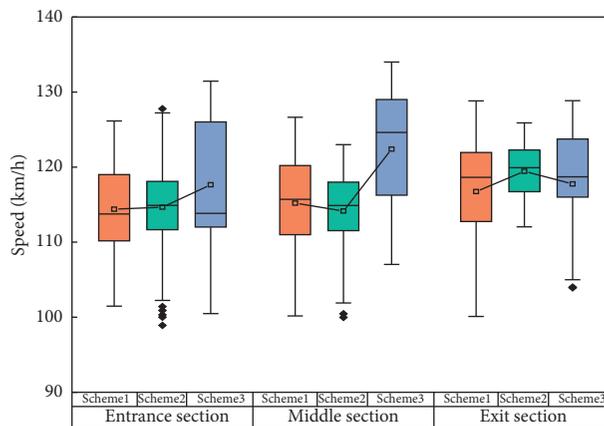


FIGURE 11: Speed changes in different tunnel sections for different right lateral clearances.

ability of the drivers of the two schemes in the left lateral clearance environment. When the right lateral clearance is widened from 1.75 m to 2.00 m, the driver's lane keeping ability does not improve significantly, until it continues to increase to 2.25 m, and the driver's lane keeping ability improves.

The driving performance results under different lateral clearances are as shown in Table 9. The steering wheel angular velocity index is not considered, because it is not significantly different between different schemes and has poor sensitivity.

TABLE 6: Descriptive statistics of speed indicators for different design speed schemes.

	Scenario scheme	Average speed	Speed standard deviation
Left lateral clearance	Scenario 1	61.2	3.7
	Scenario 2	76.8	5.2
	Scenario 3	119.2	8.7
Right lateral clearance	Scenario 2	83.1	4.8
	Scenario 3	117.7	6.7

TABLE 7: Paired sample *t*-test results.

Paired samples	<i>T</i>	<i>P</i>
Scheme 1-Scheme 2	0.033	0.974

TABLE 8: Analysis of variance afterwards multiple comparison results.

Number ( <i>I</i> )	Number ( <i>J</i> )	Mean difference ( <i>I</i> - <i>J</i> )	Standard deviation	Obvious
Scheme 1	Scheme 2	-0.069	0.109	0.527
	Scheme 3	-0.269	0.109	0.016*
Scheme 2	Scheme 3	-0.199	0.109	0.072

TABLE 9: Driving performance statistics of small car drivers with different lateral clearances.

	Scheme number	Operating speed (km/h)	Speed increase or decrease ratio (%)	Speed standard deviation (km/h)
Right lateral clearance	Scheme 1	123.4	—	6.7
	Scheme 2	121.2	1.8↓	5.6
	Scheme 3	128.0	3.7↑	8.5
Left lateral clearance	Scheme 1	121.6	—	8.7
	Scheme 2	126.3	3.9↑	7.6

Note. “↑” and “↓” indicate that, relative to Scheme 1, the indicator is increased or decreased.

## 5. Conclusions

In modern tunnels, lateral clearance designs contribute significantly to traffic safety. Effective lateral clearance and recovery area most likely benefit reducing driving tension and accident probability. In this paper, the driving behavior and the changing law of vehicle operation under different lateral clearances of tunnels are studied. The field tests of five lateral clearance schemes in eight tunnels are carried out for data collection. The operating speed, speed standard deviation, and steering wheel angle which can reflect the driving stability and the lane keeping control ability of drivers are taken as the characterizing parameters of driving performance. There is a multitude of factors that may play a role, and different combinations can yield different results. This notion is supported by the interaction influence analysis of the indicators and lateral clearances.

In the left lateral clearance environment, compared to the lateral clearance with 1.25 m, the operating speed of the lateral clearance with 1.50 m is increased by 3.9%, and the speed standard deviation is relatively small. Thus, the design of the left lateral clearance with 1.50 m has improved the driver performance. This could be a hint that such wider lateral clearance is beneficial to ensure that drivers maintain higher speed and better safety.

With respect to the right lateral clearance, the drivers travel at a similar operating speed under the lateral clearance with 1.75 m and 2.00 m. However, the speed standard deviation of the latter lateral clearance is relatively low with only 5.6 km/h. By contrast, the operating speed of the lateral clearance with 2.25 m is 3.7% higher than that of 1.75 m. Unsurprisingly, the speed standard deviation increases instead. It can be concluded that the operating speed has little change when the right lateral clearance is increased from 1.75 m to 2.00 m, but the driver’s speed retention ability is significantly improved. As a result, the lateral clearance up to 2.25 m leads to a much higher operating speed and speed standard deviation. This change, coupled with a relatively complex environment in tunnels, may add safety risks. This notion is supported by the fact that, by driving in the too wide lateral clearance of tunnels, drivers easily tend to fall into higher driving freedom and the driver’s ability to maintain speed becomes weaker.

In addition, the finding in scenarios of different design speeds with different lateral clearances also indicates that the speed limit has a greater impact on the operating speed. The operating speed of the right side is higher and more stable when the design speed is 100 km/h. However, further increasing the speed limit with a wider left or right lateral clearance has little effect on driving behavior.

This study provides reasonable suggestions for the setting of lateral clearances. It is suggested that, by setting the reasonable lateral width of tunnel at different design speeds, the vehicle cannot reduce speed when passing the tunnel, thus reducing the driving load, so as to further ensure the driving safety. Given that various factors may affect the results, the influence of other factors, such as horizontal and vertical alignments, illuminations, and individual driver differences, was not explored here. Unlike a simulator test in which it is easier to control the independent variables, studying these complex interactions in a real-world driving environment is quite challenging. Because the study was limited to the actual conditions, only 5 small-sized vehicles were compared for the left and right lateral clearances, and the subjects were mainly male drivers. In the future research, the sample size should be further expanded, large-scale vehicle experiments should be added, and a variety of tunnel scenarios with different lateral clearances should be constructed to improve the universality of the conclusions.

### Data Availability

All data and models generated or used during the study are mentioned in the submitted article.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

### Acknowledgments

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