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RESEARCH ARTICLE

Modeling the Risks of Lane-Changing on Adjacent Sections of Tunnel Entrances

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ABSTRACT The entrances of tunnels are generally considered to be accident-prone locations, and accidents related to this area mainly include rear-end and sideswipe crashes, which are also associated with lane-changing behaviours. Despite the extensive literature on the safety of lane-changing, little attention has been given to lane-changing behaviours in front of the tunnel entrance. To this end, this study investigates the contributing factors to the potential risk status of lane-changing, taking into account lane-changing scenarios and the distance to tunnel entrances. Vehicular trajectory data on adjacent sections of tunnel entrances was collected by naturalistic driving tests, and 615 lane-changing scenarios were extracted for analysis. Furthermore, lane-changing risk margin (LCRM) is proposed to estimate whether there is at potential risk during lane-changing. To verify the influence of risk factors on the safety of lane-changing on adjacent sections of tunnel entrances, a mixed logit model is established for different lane-changing scenarios and distance levels to tunnel entrances. The model estimation results indicate that the leading vehicles in the current lane and target lane (defined as CLV and TLV, respectively) significantly affect the risk of lane-changing, with the presence of CLV increasing the probability of performing risky lane-changing as approaching the tunnel entrance, while the presence of TLV instead reduces the probability of performing risky lane-changing behaviour. The distance to the tunnel entrance also has a significant impact on the risk of lane-changing, and the probability of the risk of lane-changing is higher at relatively close distances than at relatively long distances. Moreover, on adjacent sections of tunnel entrances, drivers mainly change lanes to the left, which is likely to be related to safer driving on the left. This implies that drivers approaching the tunnel may try to achieve better driving conditions before entering the tunnel by changing lanes in view of the complex driving conditions inside the tunnel.

INDEX TERMS Lane-changing, crash risk, random parameter, mixed logit model, adjacent sections of tunnel entrances.

I. INTRODUCTION

According to the World Health Organization [1] (Organization, 2018), approximately 1.3 million people die each year as a result of road traffic crashes. In addition to the number of accidents, it is also worth noting the consequences and extent of the damage. In the accident statistics for ordinary and special sections (including tunnels, bridges, interchanges, and their composite structures), the lowest proportion of accidents occurred in tunnels (3.48%), but at the same time, the proportion of accidents resulting in deaths or injuries in tunnels is relatively high (86.57%) in light of Sun, Liu, Li, Tang and Fang [2]. Therefore, tunnels remain a concerning traffic safety risk factor.

In terms of traffic safety, the visual conditions are poor in the tunnel entrance and interior, which has a negative impact on driving. Several studies have confirmed that the probability of a crash in a tunnel is lower than that of an open road, but a crash in a tunnel may be more serious [3], [4]. Researchers have generally concluded that the entrances and exits of tunnels are accident-prone locations. The crash rate of entrances and exits is obviously higher than that of the inner zones [3], [5], [6], [7], [8], and the probability of crashes at the tunnel entrance is higher than that of the tunnel exit [9].

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The high crash rate in the adjacent area of the tunnel is attributed to visual adaptation difficulties (e.g., black-hole effect) [10], [11], lack of vigilance, failure to maintain a safe distance from the vehicle in front [8], and psychological tension of drivers and the sudden transition of the environment [12], [13]. Furthermore, traffic crashes occur more frequently in the daytime because of the sharp transitions in lighting inside and outside the tunnel [14].

Tunnel-related accidents mainly include head-on collisions, sideswipes, rear-end collisions, bumping, scrapes, rollovers, and fires. According to data on traffic accidents in tunnels, rear-end accidents account for the highest proportion of all tunnel accidents at 80%, followed by sideswipe accidents (9% of all tunnel accidents) [7]. Meanwhile, lane-changing manoeuvres are associated with rear-end and sideswipe crashes [15]. It is possible to speculate that the high crash rate at the entrance of the tunnel may be linked to the lane-changing behaviour of drivers in this area, to some extent. In addition, [16] found that drivers frequently change lanes in response to complex traffic environments, which suggests a tendency for drivers to change lanes before being confronted with complicated situations. To this end, the impact of the tunnel being approached could be useful because drivers approaching the tunnel entrance may try to achieve better driving conditions before entering the tunnel by changing lanes in view of the complex driving conditions inside the tunnel. However, the safety of lane-changing in the adjacent areas of tunnel entrance has not received sufficient attention from researchers in previous studies.

As one of the most conventional behaviours in driving, lane change manoeuvres are a key factor in traffic accidents [17]. In addition, as a complex driving task, lane-changing behaviour involves a variety of parallel subtasks (such as monitoring the forward road and surroundings, steering the vehicle, regulating the vehicle's speed, and using the turn signal), which tolerates fewer human mistakes and leads to higher safety risks. Many studies have noted the importance of lane changing in road safety [18], [19], [20], [21]. In addition to being a high-risk operation, lane changes can have a negative impact on traffic flow (e.g., cause traffic oscillations) [22], reduce traffic mobility [23], and decrease capacity [22], [24].

Drivers perform lane-changing manoeuvres either to reach a certain destination (i.e., mandatory lane-changing) or to obtain better driving conditions (i.e., discretionary lane-changing) [25]. These two types of lane-changing have different focuses: mandatory lane-changing tends to be concerned with the remaining distance in the acceleration lane and the distance to the destination, while discretionary lane-changing takes into account the selection from the candidate lanes [15]. In general, studies on lane-changing revolve approximately 3 aspects: the decision-making process of lane-changing [26], [27], [28], [29], the implementation of lane-changing [30], [31], and the impact of lane-changing [32], [33], [34]. Lane-changing behaviours can be analysed based on examining the speed [35], safe gap [36], gap acceptance, lane-changing duration, and impact on the following vehicle [37], [38]. Researchers often address driver characteristics [39], [40], [41], vehicle type [21], [42], driving context [43], [44] and weather as influencing factors associated with the success of executing a lane-change. However, studies on the safety of lane-changing in some specific driving environments (e.g., the adjacent area of tunnel entrances) are sparse or lacking.

For lane changing safety research, there are many safety evaluation indicators, such as time to collision (TTC) [45], [46], [47], [48], potential index for collision with urgent deceleration (PICUD) [49], proportion of stopping distance (PSD) [50], margin to collision (MTC) [49], difference of space distance and stopping distance (DSS) and time integrated DSS (TIDSS) [51], [52]. However, these models are designed for ordinary open roads and do not take into account the possible effects of special environments. In fact, according to Du [11], drivers will experience visual oscillations when passing through tunnel portals at a high speed, resulting in a visual problem that will extend drivers' cognition reaction period and is reflected in the equivalent duration of visual oscillation (EDVO). The EDVO may affect the results of vehicle lane-changing safety evaluation on the adjacent section of the tunnel entrances, which has not been considered in previous studies.

For tunnel driving safety research is usually carried out in zones, and the distance in front of the tunnel entrance is often defined as the access zone. The existence of the access zone provides sufficient time for drivers to stop in case of more serious consequences of stopping in the tunnel (Safety evaluation of lighting at very long tunnels on the basis of visual adaptation). It has been noted in the introduction above that the access zone, located outside the entrance to the tunnel, is a highly accident-prone area in the tunnel and that common types of accidents (including rear-end and sideswipe accidents) are associated with lane-changing. Therefore, before entering the tunnel, drivers will switch to a lane with better visibility if traffic conditions permit, in order to reduce the impact of the tunnel environment on driving safety. However, lane-changing behaviour occurring in the area in front of the tunnel entrance is hardly mentioned in the current study.

Therefore, to determine the characteristics of lane-changing manoeuvres in areas adjacent to tunnel entrances, this paper aims to investigate the contributing factors to the risks of lane-changing behaviours by taking into account the number of vehicles around the lane change vehicle and the distance from lane-changing locations to tunnel entrances. To this end, this paper first collects several naturalistic driving test datasets and extracts vehicle lane-changing data on adjacent sections of tunnel entrances. Then, the lane-changing risk margin (LCRM) is developed for vehicle groups to evaluate the risk status during lane changes. Finally, the mixed logit model is developed to investigate the

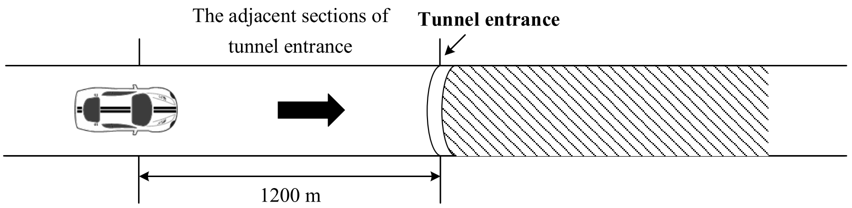

FIGURE 1. Illustration of the adjacent sections of tunnel entrances.

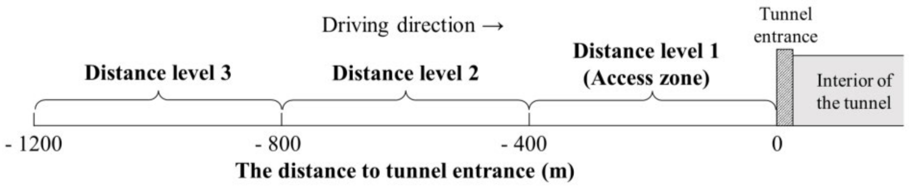

FIGURE 2. The distance level of adjacent sections of tunnel entrances.

influences of the distances to the tunnel entrances and other related factors, and their estimation results are discussed.

II. DATA PREPARATION

To achieve the research purpose, this paper first collects the real-time data of vehicle lane-changing on adjacent sections of tunnel entrances through naturalistic driving tests. According to the influence range of the tunnel on the traffic flow and driving behaviour [53], the adjacent section of the tunnel is defined as the interval from the tunnel entrance to 1200 km before the tunnel entrance, as shown in FIGURE 1. Furthermore, in order to analyze the impact of changes in driving environment during the transition from open road to tunnel on the risk of lane-changing vehicles, the adjacent section of the tunnel was divided into three equal parts considering the length of access zone [54]. The first 400 m is the area relatively close to the tunnel entrance, corresponding to the access zone, and the last 400 m is the farther area, with the control zone in the middle, as shown in FIGURE 2.

A. NATURALISTIC DRIVING TESTS

1) TEST TUNNELS

The Wu kengba Tunnel (1 337 m), Shi Menao Tunnel (1 120 m) and Pi shuangao Tunnel (750 m) were selected as the test tunnels. As depicted in FIGURE 3, the test tunnels are two-way four-lane roads with a median barrier, located at a relatively straight section of the Guangdong Jingzhu freeway. The maximum speed limit outside the test tunnel is 100 km/h, and the maximum speed limit inside the tunnel is 80 km/h with lighting.

2) PARTICIPANTS

A total of 73 drivers were invited for this test, including 48 males with an average age of 37 and an average driving age of 8.3 years, and 25 females, with an average driving

FIGURE 3. Test tunnels.

experience of more than 3 years. These drivers all had corrected visual acuity above 0.8, had no major traffic accident experience and were generally familiar with the road. They performed four naturalistic driving tests in each of the three test tunnels using the same vehicle.

3) TEST PERIOD

Due to the high risk of accidents in the tunnel during the day, the test was scheduled from October 11, 2021to November 28, 2021 between 10:00 a.m. and 3:00 p.m. All tests were conducted under favorable weather conditions, on a smooth, clean, and dry road surface.

4) TEST VEHICLE AND EQUIPMENT

The test vehicle of the present study was a Honda Accord. FIGURE 4 shows the devices equipped on the test vehicle. The velocity and position were recorded using an AKE39T Triaxial Accelerometer and GPS (WIT-IMU), respectively. The distance to the surrounding vehicles and the trajectory of surrounding vehicles were obtained by two millimeter-wave radars (ARS404) installed on the front and behind of the test

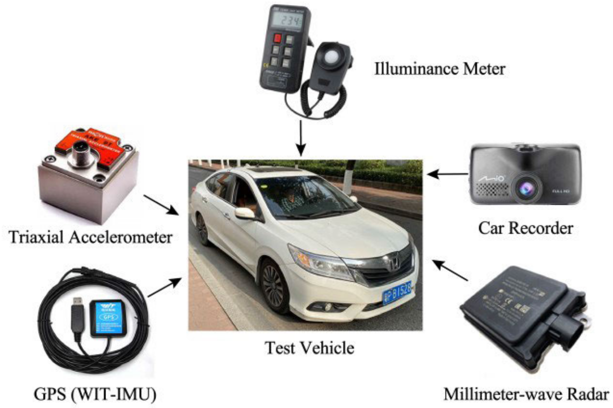

FIGURE 4. Test apparatus.

vehicle. In addition, an illuminance meter (TES-1336A) was attached near the driver's head at eye height to measure the driver's pupil luminance level. Instruments were calibrated before and after each test, and the data integrity was also verified.

5) TEST PROCEDURE AND DATA COLLECTION

Before the test, participants first drove the test vehicle for a period of time until they became accustomed to driving it. To ensure the authenticity of the collected lane-changing data on adjacent sections of the tunnel, we did not require the participants to perform an active lane-changing operation but allowed him or her to choose the driving strategy independently.

Each participant driver was instructed to drive the test vehicle through the three test tunnels twice. The staff in the test vehicle started recording the data from 1500 m before the test tunnel entrance and stopped at 300 meters inside the entrance. The test vehicle's speed, acceleration, position, and driver's pupil luminance level were documented using a CAN card, the Triaxial Accelerometer, a GPS (WIT-IMU), and the Illuminance Meter, respectively. The surrounding vehicles' speed, acceleration and relative distance between the test vehicle and the surrounding vehicles were documented using two Millimetre-wave Radars. All tests were carried out under good weather conditions, and the test road surface was flat, clean, and dry. The variation in drivers' pupil luminance is illustrated in FIGURE 5.

FIGURE 5 shows the changes in the illumination of the driver's eyes at different positions collected through natural driving experiments in the tunnel adjacent section of the test tunnel. As shown in Figure 9, the illumination of the driver's eyes is about 3600 lux on ordinary highway sections. When the vehicle travels about 430 meters away from the tunnel entrance, the illumination of the driver's eyes begins to decrease. In particular, there is a sharp decrease in illumination from 2115 lux to 21 lux in the area from 30 meters before the tunnel entrance to 40 meters inside the tunnel entrance.

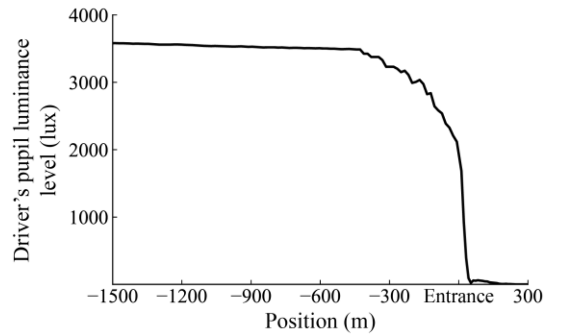

FIGURE 5. Illuminance variation curve in the adjacent section of the tunnel.

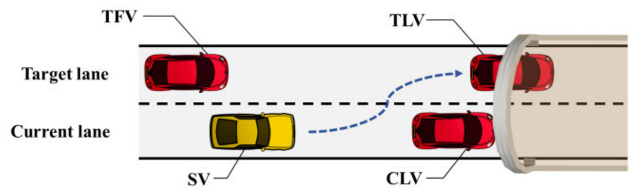

FIGURE 6. Schematic diagram of the lane-changing scenarios.

From 140 meters inside the tunnel entrance, the illumination value tends to be stable and is about 3 lux.

B. LANE-CHANGING DATA EXTRACTION

1) DEFINITION OF LANE-CHANGING SCENARIOS

The research target is the vehicle performing lane-changing manoeuvres, which we define as the subject vehicle (SV). The implementation of lane-changing generally involves two lanes, i.e., the current lane and the target lane. According to FIGURE 6, whether the SV can successfully perform a lane-changing manoeuvre is closely related to the group of vehicles around the SV in these two lanes. Among these vehicles, the leading vehicle in the current lane, the leading vehicle in the target lane and the following vehicle in the target lane are defined as CLV, TLV and TFV, respectively.

There is a limit to the influence of surrounding vehicles on the lane change vehicle, and the influence of the front vehicle on the lane-changing vehicle at a distance beyond a certain range can be ignored; thus, a certain range limit should be set, and only CLV, TLV and TFV within the range should be taken into consideration; otherwise, the corresponding position is considered empty. Previous studies have shown that the vehicle is only affected by surrounding vehicles within a longitudinal range of 200 m [55]. Therefore, we only considering the influence of the front and rear vehicles of lane-changing vehicle within 200 m during lane-changing.

2) LANE-CHANGING DATA EXTRACTION

In the dataset, the lane ID is used to mark the lane where the vehicle was located. The lane ID of a vehicle driving steadily in a particular lane does not generally change, so it can be used to quickly filter out lane-changing scenarios. As shown in FIGURE 5, we need to extract various data during the lane-changing process, which involves 4 vehicles, namely, SV, CLV, TLV and TFV, and the key is to determine the frame ID at the start and end of the lane-changing. The process of extracting the lane-changing data is outlined as follows.

Step 1: Identify the SV and determine the vehicle ID of the CLV, TLV and TFV. First, quickly locate the lane-changing scenario of SV by searching for changes in the lane ID. After the SV is identified, the vehicle ID of the CLV, TLV and TFV can be determined by the lane ID and the relative positions of each vehicle before the lane ID of the SV changes.

Step 2: Determine the frame ID at the start and end of the lane-changing. On the expressway, lane-changing durations are typically in the range of 3 to 10 seconds. Therefore, it can be in the range of 250 frames (the frame rate of data recording is 25 frames per second) before and after the frame ID where the lane ID changes. Furthermore, as the test areas are relatively straight road sections, it is reasonable to assume that the lateral acceleration of the SV is approximately to zero at these two points.

FIGURE 7 shows an example of the process for determining the starting and ending points of lane-changing. It should be noted that when determining the starting and ending points of a lane-changing, it is not just the change in lateral acceleration that is relied upon but also the lane ID and position information. This is because the lateral acceleration of the vehicle may vibrate around zero and needs to be analysed in conjunction with the lane ID and lateral position. In FIGURE 6, the lateral acceleration of the SV was also equal to zero at one point during the process of lane-changing; however, the lane ID had just changed, and the lateral position was still fluctuating as the time, indicating that the SV had not yet reached a stable state and the lane-changing process was not complete, so the ending point of the lane-changing should be determined at the position where the next lateral acceleration is close to zero.

Through data integration, 615 lane-changing scenarios that occurred in adjacent sections of the tunnel entrance were finally obtained, with an average lane-changing time of 5.5 seconds. It should be noted that the lane change scenarios used for analysis only involve small cars as surrounding vehicles, and scenarios where the surrounding vehicles are large vehicles are excluded. Due to the limited amount of data where the surrounding vehicles are large vehicles, only 10 scenarios were collected.

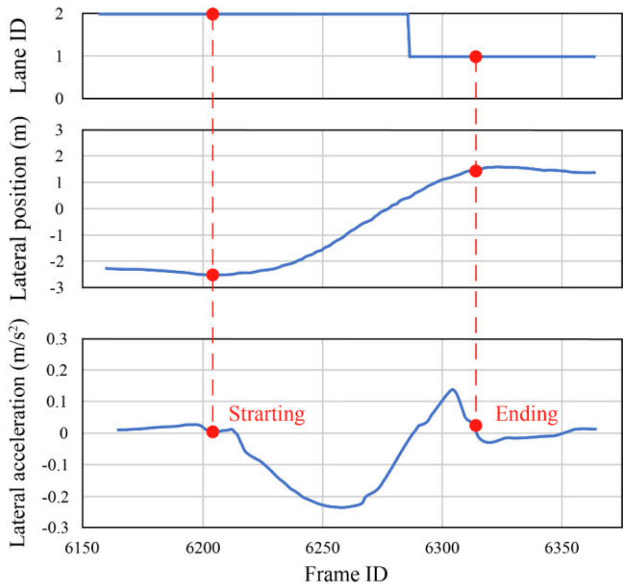

FIGURE 7. Example of determining the starting and ending points of lane-changing.

III. METHODOLOGY

A. LANE-CHANGING RISK MARGIN (LCRM)

The risk of adjacent vehicles in the lane is the possibility of a two-vehicle collision. Assuming that the leading vehicle suddenly brakes and the following vehicle also brakes quickly after reacting, the distances travelled by the two vehicles during this period are $[v_{n-1}(t)]^2/2a_{n-1}(t)$ and $v_n(t) \cdot (\tau_1 + \tau_2) + [v_{n-1}(t)]^2/2a_{n-1}(t)$, respectively. At the same time, if the distance between the two vehicles at the initial position is d_n, then the following conditions should be met to prevent the two from collision:

$$v_n(t) \cdot (\tau_1 + \tau_2) + \frac{[v_n(t)]^2}{2a_n(t)} \leq \frac{[v_{n-1}(t)]^2}{2a_{n-1}(t)} + d_n \tag{1}$$

The above formula can also be written as:

$$\frac{v_n(t) \cdot (\tau_1 + \tau_2) + \frac{[v_n(t)]^2}{2a_n(t)} - \frac{[v_{n-1}(t)]^2}{2a_{n-1}(t)}}{d_n} \leq 1.0 \tag{2}$$

Therefore, the risk margin can be described as follows:

$$RM_{\mathrm{n}-1,n}(\tau, t) = \frac{v_n(t) \cdot (\tau_1 + \tau_2) + \frac{[v_n(t)]^2}{2a_n(t)} - \frac{[v_{n-1}(t)]^2}{2a_{n-1}(t)}}{d_n} \tag{3}$$

where $RM_{n-1,n}(\tau,\ t)$ is the risk margin between vehicle $n-1$ and n; $v_n(t)$ is the speed of the following vehicle; $v_{n-1}(t)$ is the speed of the leading vehicle; $a_n(t)$ is the deceleration of the following vehicle; $a_{n-1}(t)$ is the deceleration of the lead vehicle (the maximum deceleration rate of the vehicle is set to 3.4 m/s^2); d_n is the relative distance between the two vehicles; τ is the response time, including the response time of the driver (τ_1 is set to 1.5 s) and the response time of the brake system (τ_2 is set to 0.15 s).

Safety is ensured when:

$$RM_n(\tau, t) \leq 1.0 \tag{4}$$

However, the above risk margin is for two adjacent vehicles in same lane. In the lane-changing scenario, more vehicles are involved, and the interaction between each vehicle should be fully considered. Therefore, a lane-changing risk margin (LCRM) is proposed to evaluate the risk of lane-changing, which considers the effect of the surrounding vehicles on the

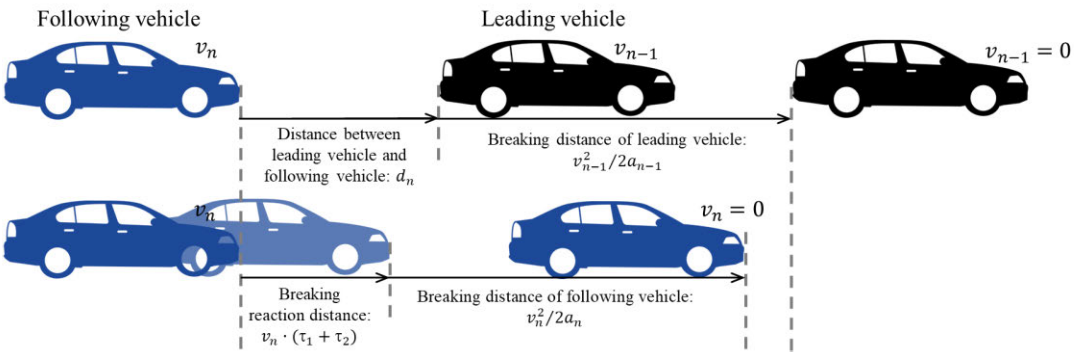

FIGURE 8. **Definitions of risk margin.**

driving risk of SV. When all of $RM_{CLV,SV}$, $RM_{TLV,SV}$ and $RM_{SV,TFV}$ are less than 1, it indicates a low risk for the lane change vehicle SV and $LCRM$ is equal to 0. However, when one of $RM_{CLV,SV}$, $RM_{TLV,SV}$ and $RM_{SV,TFV}$ is greater than 1, it indicates a high risk for the lane change vehicle SV and $LCRM$ is equal to 1. The LCRM is defined as:

$$LCRM=\begin{cases}0, & \text{if } RM_{CLV,SV}, RM_{TLV,SV}, RM_{SV,TFV}\leq 1\\ 1, & \text{otherwise}\end{cases} \tag{5}$$

According to relevant studies, visual problems accounted for by drivers near tunnel entrances will lead to the prolongation of drivers' cognitive reaction time. Therefore, the stopping sight distance should be increased at the entrance of the tunnel to ensure driving safety. The increased stopping sight distance can be calculated by the equivalent duration of visual oscillation, which is the visual adaptation time for drivers. Du [11] estimates the relationship between the pupil illuminance transition and visual adaptation time at the tunnel entrances as:

$$t_c=0.2591+4.044\cdot 10^{-4}\cdot k-4.4514\cdot 10^{-8}\cdot k^2 \tag{6}$$

where t_c is the equivalent duration of visual oscillation and k is the rate of change of driver's eye illumination. Considering that when there is no significant transition in illumination, a driver does not feel discomfort, and it has no effect on driving, so when $k=0$, t_c takes the value of 0.

The k can be calculated as:

$$k=\frac{l[x(t_i)]-l[x(t_{i-1})]}{|x(t_i)-x(t_{i-1})|} \tag{7}$$

where $l[x(t_i)]$ is the illumination of vehicle at $x(t_i)$ and t_i is the time step.

Therefore, the calculation of the above RM should also considering the driver's visual adaptation time at the tunnel entrances:

$$RM_{n-1,n}(\tau,t)=\frac{v_n(t)\cdot(\tau_1+\tau_2+t_c)+\frac{[v_n(t)]^2}{2a_n(t)}-\frac{[v_{n-1}(t)]^2}{2a_{n-1}(t)}}{d_n} \tag{8}$$

B. MIXED LOGIT MODEL

The mixed logit model is evolved from multinomial logit model, which solves the limitation that the multinomial Logit model fails to consider individual differences and the IIA assumption. The research object of this paper is the risk status of vehicle lane-changing on the adjacent section of the tunnel entrances, that is, the probability of lane-changing maneuvers with or without risk.

Before introducing the mixed logit model, this section begins with the basic form of the multinomial logit model, in which the random terms are assumed to be independent of each other and obey the extreme value I-type distribution at the same time. The utility function of the multinomial logit model is shown as equation (10):

$$\begin{cases}LCRM_{i0}=\beta_0'\cdot x_{i0}+\varepsilon_{i0}\\ LCRM_{i1}=\beta_1'\cdot x_{i1}+\varepsilon_{i1}\end{cases} \tag{9}$$

where i indexes the observation; $LCRM_{i0}$ (or $LCRM_{i1}$) is the utility function of lane changing behavior i with risk state = 0 or 1 (1 means risky, and 0 means riskless); β_0' (or β_1') is the parameter that affects the risk of lane-changing vehicle; x_{i0} (or x_{i1}) are the independent variables of the factors affecting the risk state of vehicle lane-changing; and ε_{i0} (or ε_{i1}) is the error term.

Assuming that ε_{i0} and ε_{i1} are independently and identically distributed with identical extreme value distribution. Therefore, the CDF is $F(-\varepsilon_j)=exp(-exp(-\varepsilon_j))$. Based on this specification, the probability of risk state of vehicle lane-changing is:

$$\begin{aligned}P(RS=j)&=P(LCRM_{ij}>LCRM_{ik}),\forall \text{k}\neq j\\ &=P_j(i)=\frac{\exp(\beta_j'\cdot x_{ij})}{\sum_{m=0}^{1}\exp(\beta_m'\cdot x_{mj})},\quad j=0,1\end{aligned} \tag{10}$$

Apart from the unfixed parameters, the overall form of the random parameter Logit model is basically the same as that of the polynomial Logit model. The parameters of the mixed logit model usually obey a certain distribution, that is, $\beta_j\sim f(\beta_j|\theta)$, and common distributions include normal distribution, uniform distribution, etc. The k-th component of parameter β_{ik} is:

$$\beta_{\text{ik}} = \beta_k + \sigma_k \cdot v_{ik} \tag{11}$$

where β_k is the mean of the k-th independent variable parameter; σ_k is the standard deviation of the k-th independent variable parameter; v_{ik} is unobservable random effects of sample i with mean and variance of 0 and 1, respectively.

Since the probability function of the random parameter Logit model is non-closed, it cannot be solved directly by calculating the integral, but can be solved by the Monte Carlo method. Monte Carlo method carries out random simulation with the help of computer, sampling the probability density function multiple times, and using the simulated probability mean as the approximate solution of the integral. This paper will use NLOGIT 6 for estimating parameters, using Mersenne Twister as the sampling method for simulation-based calculations.

For the validity of the model, use the chi-square (χ^2) to test. These test statistic was introduced by Pearson [56]. The Eq. 13 is the calculation formula of the test statistic, which obeys the chi-square distribution with k-1 degrees of freedom when the relevant assumptions are true.

$$\chi^2 = \sum_{\text{i}=1}^{k} \frac{(f_i - np_i)^2}{np_i} \tag{12}$$

where f_i is the group frequency; np_i is the theoretical frequency.

IV. MODEL RESULT

Based on the research objective, this paper focuses on discretionary lane-changing, which occurs in pursuit of faster speed or more freedom to drive when encountering a slower vehicle ahead. Therefore, it should be ensured that the vehicle changes lanes under the premise of being restricted by the leading vehicle, i.e., the presence of CLV in lane-changing scenarios is mandatory. In fact, most vehicles would not normally change lanes in the absence of CLV, except for the need for a mandatory lane-changing or to change into the fast lane. Therefore, it is reasonable to select all lane-changing scenarios with CLV for study. In addition, for research purposes, we concentrate on the relationship between whether the front vision conditions are optimized after lane-changing and the risk of lane-changing, which is closely related to the existence of TLV. Therefore, according to the presence of TLV, we divided the lane-changing scenarios into two patterns for research, with examples of each pattern and their proportions shown in FIGURE 9.

In the previous section, we defined the adjacent sections of tunnel entrances (i.e., the 1200 m section before the tunnel entrances) and divided it into 3 equal parts. For the convenience of explanation, we define these three parts as distance levels 1, 2 and 3, representing the distance to the tunnel entrances in ascending order (as shown in FIGURE 2), with proportions of 28.36%, 50.75% and 20.89% in each level, respectively.

Based on the collected data and research purposes, we selected 22 influencing factors. According to the classification of lane-changing patterns and distance levels, the summary of these influencing factors is sorted in TABLE 1 and TABLE 2, respectively.

Before the estimation of parameters, a collinearity diagnostic is required for variables to ensure that they do not have severe collinearity. NLOGIT 6.0 was used to estimate the parameters. For the selection of random parameters, it is assumed that all significant variables are random parameters first and then filtered in turn; only the parameters of interest and the parameters that passed the significance test were retained as random parameters. Finally, the validity of the model was evaluated by conducting a chi-square test on the fitted results of the model. Taking pattern 1 as an example, in the mixed logit model estimation, χ^2 is 96.43 with 11 degrees of freedom, which is greater than the critical value of 24.73 (significant level = 0.01), indicating that the overall validity of the model has passed the test. McFadden's $\rho^2 = 0.75$, which suggests good statistical fits of the estimated model. The fitting models under other patterns or distance levels also passed the tests, and the results of parameter estimation are summarized in TABLE 3 and 4.

V. DISCUSSION

A. LANE-CHANGING SCENARIOS

TABLE 5 presents the statistics of LCRM in different lane-changing scenarios. The mean of the LCRM in pattern 2 is higher than that in pattern 1, and the standard deviation of pattern 2 is lower than that of pattern 1. This may imply a higher probability of performing risky lane-changing on adjacent sections of the tunnel entrances in the absence of TLV.

In the following, the impact of different influencing factors on the risk of lane-changing in different lane-changing scenarios will be analysed in conjunction with the results of the mixed logit model parameter estimation for the 2 lane-changing patterns summarized in TABLE 3.

First, the contributing factors associated with lane-changing scenarios are interpreted as follows:

(1) The impact of TLV in pattern 1: In pattern 1, both the longitudinal velocity of the TLV (V8) and the longitudinal distance between SV and TLV (V9) at the start of lane-changing are significant factors influencing the risk of lane-changing. With LCRM=1, the coefficient of V8 is positive, indicating that the greater the longitudinal velocity of the TLV is, the greater the probability of risky lane-changing behaviour. The coefficient of V9 is negative, indicating that the greater the longitudinal distance between SV and TLV is, the lower the probability of risky lane-changing behaviour. Therefore, it is necessary to be vigilant that drivers ignore the risks and make unsafe lane changes when TLVs are travelling at higher speeds and when there is a smaller longitudinal distance between the SV and TLV.

(2) The impact of TFV: V5 (presence of TFV) is a significant factor on the risk of lane-changing, both in

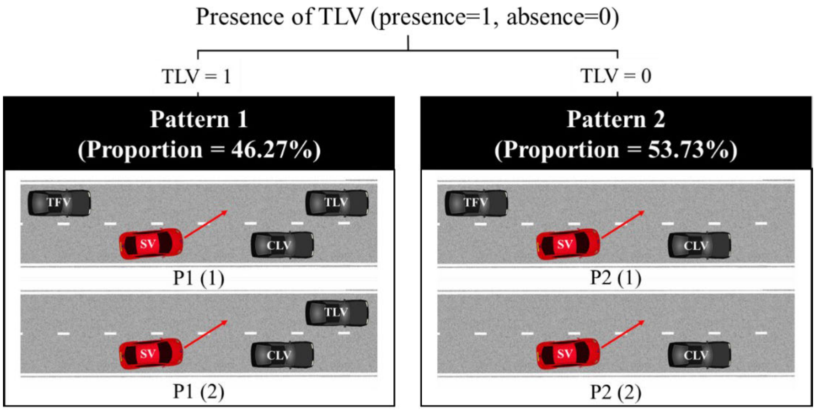

FIGURE 9. Example of 2 lane-changing patterns and their proportions.

TABLE 1. Summary of statistics of variables (disaggregated by lane-changing patterns).

Variables			Pattern 1		Pattern 2	
			Mean	Std. Dev	Mean	Std. Dev
V1:	Distance level to tunnel entrance (m):	Distance ⩽ 400	0.19	0.40	0.36	0.48
V2:		400 < distance ⩽ 800	0.65	0.48	0.39	0.49
V3:		800 < distance ⩽ 1200	0.16	0.37	0.25	0.43
V4:	Lane-changing patterns:	Presence of TLV (presence=1, absence=0)				
V5:		Presence of TFV (presence=1, absence = 0)	0.65	0.48	0.92	0.28
V6:		Longitudinal velocity of CLV at start of lane-changing (m/s)	21.33	10.71	20.97	4.81
V7:		Longitudinal distance to CLV at start of lane-changing (m)	54.56	28.97	69.21	38.11
V8:		Longitudinal velocity of TLV at start of lane-changing (m/s)	25.86	10.81		
V9:		Longitudinal distance to TLV at start of lane-changing (m)	62.05	49.42		
V10:		Longitudinal velocity of TFV at start of lane-changing (m/s)	25.96	33.06	20.89	2.66
V11:		Longitudinal distance to TFV at start of lane-changing (m)	1.06	0.35	25.04	22.37
V12:		Lane-changing duration (s)	5.44	2.11	5.60	2.06
V13:		Distance traveled during entire lane-changing process (m)	158.90	148.27	156.99	84.02
V14:		Lane-changing direction (left side = 1, right side = 0)	0.71	0.46	0.92	0.28
V15:		Average longitudinal velocity of lane-changing (m/s)	23.51	3.83	25.03	3.49
V16:		Average lateral velocity of lane-changing (m/s)	0.30	0.61	0.41	0.44
V17:		Maximum lateral acceleration of lane-changing (m/s^2)	0.33	0.40	0.32	0.30
V18:	Lane-changing gap (m):	Gap⩽50	0.29	0.46	0.16	0.12
V19:		50<Gap⩽100	0.42	0.49	0.18	0.13
V20:		100<Gap⩽150	0.19	0.40	0.21	0.23
V21:		150<Gap⩽200	0.06	0.25	0.12	0.11
V22:		Gap>200	0.03	0.18	0.33	0.32

patterns 1 and 2. Moreover, in these two patterns, the coefficient of V5 at LCRM = 0 is negative, which indicates that the risk of lane-changing behaviour in lane-changing scenarios with TFV is higher than that without TFV. The average elasticity of V5 at LCRM=1 is 0.21% and 10.54% at P1 and P2, respectively, suggesting that the probability of risky lane-changing behaviour in the presence of TFV is elevated by 0.21% and 10.54% in patterns 1 and 2, respectively, compared to the absence of TFV.

(3) **The impact of CLV**: The effect of V6 (the longitudinal velocity of CLV) and V7 (the distance between SV and CLV) is significant, and both capture heterogeneity from the probability distribution of their random parameters (shown in FIGURE 10). In pattern 1 and LCRM = 1, the random

TABLE 2. Summary of statistics of variables (disaggregated by distance level to tunnel entrance).

Variables			Distance leve 1		Distance leve 2		Distance leve 3	
			Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
V1:	Distance level to tunnel entrance (m):	Distance ⩽ 400						
V2:		400 < distance ⩽ 800						
V3:		800 < distance ⩽ 1200						
V4:	Lane-changing patterns:	Presence of TLV (presence=1, absence=0)	0.32	0.47	0.59	0.49	0.36	0.48
V5:		Presence of TFV (presence=1, absence=0)	0.84	0.37	0.74	0.44	0.86	0.35
V6:	Longitudinal velocity of CLV at start of lane-changing (m/s)		19.29	5.01	21.69	10.41	22.30	3.13
V7:	Longitudinal distance to CLV at start of lane-changing (m)		68.21	32.15	55.74	33.11	70.83	39.68
V8:	Longitudinal velocity of TLV at start of lane-changing (m/s)		24.55	6.08	26.69	12.95	24.10	2.01
V9:	Longitudinal distance to TLV at start of lane-changing (m)		79.37	36.36	60.76	54.32	46.41	35.31
V10:	Longitudinal velocity of TFV at start of lane-changing (m/s)		18.90	3.56	21.21	3.04	21.93	3.12
V11:	Longitudinal distance to TFV at start of lane-changing (m)		21.35	23.60	22.61	21.10	36.53	37.13
V12:	Lane-changing duration (s)		4.98	1.82	5.29	2.00	6.84	2.09
V13:	Distance traveled during entire lane-changing process (m)		126.86	51.12	131.03	49.73	265.15	207.24
V14:	Lane-changing direction (left side = 1, right side = 0)		0.95	0.22	0.74	0.44	0.86	0.35
V15:	Average longitudinal velocity of lane-changing (m/s)		23.83	3.63	24.06	3.72	25.64	3.63
V16:	Average lateral velocity of lane-changing (m/s)		0.47	0.58	0.31	0.54	0.32	0.41
V17:	Maximum lateral acceleration of lane-changing (m/s^2)		0.55	0.52	0.22	0.20	0.27	0.18
V18:	Lane-changing gap (m):	Gap ⩽ 50	0.12	0.10	0.24	0.43	0.07	0.26
V19:		50 < Gap ⩽ 100	0.16	0.37	0.21	0.41	0.21	0.41
V20:		100 < Gap ⩽ 150	0.11	0.31	0.09	0.28	0.07	0.26
V21:		150 < Gap ⩽ 200	0.05	0.22	0.03	0.17	0.30	0.21
V22:		Gap > 200	0.56	0.47	0.44	0.50	0.34	0.48

parameter V6 obeys a normal distribution with a mean of 0.31 and a standard deviation of 0.26. The probability of this parameter being less than 0 is 11.75%, which implies that in pattern 1, as the longitudinal velocity of the CLV increases, there is a 11.75% lower probability of vehicles engaging in risky lane-changing behaviour and a 88.25% higher probability of vehicles engaging in risky lane-changing behaviour. In pattern 2, the same can be obtained; as the distance between SV and CLV increases, the 25.25% probability of vehicles performing risky lane-changing behaviours is lower, while the74.25% probability of vehicles performing risky lane-changing behaviours is higher.

(4) **The impact of SV**: The parameter estimation results of the mixed logit model indicate that the greater the maximum lateral acceleration of lane-changing (V17) of the SV, the lower the probability of risky lane-changing behaviour, regardless of pattern 1 or 2. In pattern 2, the average lateral velocity of lane-changing (V16) of the SV is negatively correlated with the probability of performing risky lane-changing behaviour. Therefore, the greater the maximum lateral acceleration and the average lateral velocity of lane-changing are, the more conducive it is to ensuring the safety of lane-changing.

Then, other factors contributing to the risk of lane-changing are illustrated:

(1) The impact of distance level in different lane-changing scenarios: When modelling, we take V1 (distance to tunnel entrance ≤ 400 m) as the benchmark variable of distance level, corresponding to distance level 1. TABLE 6 summarizes the average elasticity of the other two variables related to distance level (V2 and V3, corresponding to distance level 2 and distance level 3, respectively). In pattern 1, compared with distance level 1, the probability of risky lane-changing behaviour performing in distance level 2 and distance level 3 is reduced by 0.86% and 0.66%, respectively. This suggests that in the presence of TLVs, the probability of risky lane-changing occurring in the access zone is slightly higher than that in other areas adjacent to the tunnel entrance. In pattern 2, the probability of risky lane-changing in distance level 3 increases by 0.36% compared to distance level 1, which is approximately the same. The probability of risky lane-changing behaviour at distance level 2 decreased

TABLE 3. Results of parameter estimation (disaggregated by lane-changing patterns).

Lane-changing scenarios	LC RM	Variables	Coefficient	Standard Error
Pattern 1	0	V2: Distance level to tunnel entrance (400 m $<$ distance $\leqslant$ 800 m)	0.46***	0.16
		V3: Distance level to tunnel entrance (800 m $<$ distance $\leqslant$ 1200 m)	0.66***	0.24
		V12: Lane-changing duration (s)	0.06***	0.02
		Random parameters (assumed to be normally distributed):		
		V5: Presence of TFV (presence = 1, absence = 0)	-0.37***	0.13
		Standard deviation for the random parameter (V5)	0.17	0.02
	1	V8: Longitudinal velocity of TLV at start of lane-changing (m/s)	0.31**	0.12
		V9: Longitudinal distance to TLV at start of lane-changing (m)	-0.26***	0.09
		V17: Maximum lateral acceleration of lane-changing (m/s^2)	-0.60***	0.21
		Random parameters (assumed to be normally distributed):		
		V6: Longitudinal velocity of CLV at start of lane-changing (m/s)	0.31*	0.63
		Standard deviation for the random parameter (V6)	0.26*	0.14
		AIC	354.50	
		BIC	382.40	
		McFadden ρ^2	0.75	
		χ^2	2.43	
Pattern 2	0	V3: Distance level to tunnel entrance (800 m $<$ distance $\leqslant$ 1200 m)	-0.39***	0.04
		V6: Longitudinal velocity of CLV at start of lane-changing (m/s)	-0.08***	0.14
		V12: Lane-changing duration (s)	0.19***	0.09
		Random parameters (assumed to be normally distributed):		
		V5: Presence of TFV (presence = 1, absence = 0)	-1.66***	0.33
		Standard deviation for the random parameter (V5)	0.11	0.05
	1	V2: Distance level to tunnel entrance (400 m $<$ distance $\leqslant$ 800 m)	-0.64***	0.08
		V13: Lane-changing direction (left side = 1, right side = 0)	0.79***	0.53
		V17: Maximum lateral acceleration of lane-changing (m/s^2)	-0.93***	0.59
		V16: Average lateral velocity of lane-changing (m/s)	-1.83***	0.74
		Random parameters (assumed to be normally distributed):		
		V7: Longitudinal distance to CLV at start of lane-changing (m)	0.21***	0.03
		Standard deviation for the random parameter (V7)	0.31***	0.02
		AIC	370.70	
		BIC	400.20	
		McFadden ρ^2	0.67	
		χ^2	1.99	

Notes: *, **, and *** denote the statistical significance at 0.1, 0.05 and 0.01 levels, respectively.

by 2.76%. This indicates that in the absence of TLV, vehicles have a tendency to perform risky lane changes in the access zone compared to distance level 2, which is slightly further away from the tunnel entrance.

(2) **The impact of lane-changing duration in different lane-changing scenarios**: The risk status of the lane-changing behaviour is significantly related to the lane-changing duration (V12) in both patterns 1 and 2. The results of parameter estimation reveal that the longer the lane-changing duration is, the lower the probability of performing a risk-free lane-changing.

(3) **The impact of lane-changing direction in pattern 2**: In pattern 2, the effect of lane-changing direction (V13) on the risk of lane-changing is significant. The results of the parameter estimation demonstrate an increased probability of risky lane-changing for turning left compared to turning right. However, lane-changing on the adjacent section of the tunnel is still dominated by changing lanes to the left, with 71% and

TABLE 4. Results of parameter estimation (disaggregated by distance level to tunnel entrance).

Distance level to tunnel entrance	LC RM	Variables	Coefficient	Standard Error
Distance level 1	0	V13: Lane-changing direction (left side = 1, right side = 0)	1.41***	0.42
		Random parameters (assumed to be normally distributed):		
		V4: Presence of TLV (presence = 1, absence = 0)	0.33***	0.12
		Standard deviation for the random parameter (V4)	0.62	0.37
		V5: Presence of TFV (presence = 1, absence = 0)	-1.34***	0.33
		Standard deviation for the random parameter (V5)	0.48	0.16
		V12: Lane-changing duration (s)	0.09***	0.01
		Standard deviation for the random parameter (V14)	0.26	0.30
	1	V14: Distance traveled during entire lane-changing process (m)	1.23***	0.10
		V16: Average lateral velocity of lane-changing (m/s)	0.34***	0.29
		Random parameters (assumed to be normally distributed):		
		V6: Longitudinal velocity of CLV at start of lane-changing (m/s)	0.29***	0.22
		Standard deviation for the random parameter (V6)	0.13***	0.08
		V15: Average longitudinal velocity of lane-changing (m/s)	0.51***	0.59
		Standard deviation for the random parameter (V17)	0.17***	0.07
		AIC	342.20	
		BIC	468.80	
		McFadden ρ^2	0.79	
		χ^2	2.78	
Distance level 2	0	V6: Longitudinal velocity of CLV at start of lane-changing(m/s)	-1.18*	0.65
		V17: Maximum lateral acceleration of lane-changing (m/s2)	1.09***	0.48
		Random parameters (assumed to be normally distributed):		
		V4: Presence of TLV (presence = 1, absence = 0)	-0.67***	0.56
		Standard deviation for the random parameter (V4)	0.66	0.26
		V5: Presence of TFV (presence = 1, absence = 0)	-1.68***	0.89
		Standard deviation for the random parameter (V5)	0.11***	0.58
	1	V7: Longitudinal distance to CLV at start of lane-changing(m)	-0.64***	0.09
		V14: Distance traveled during entire lane-changing process(m)	0.21**	0.09
		V15: Average longitudinal velocity of lane-changing (m/s)	-1.17***	0.71
		V22: Lane-changing gap＞200	0.40***	0.04
		AIC	348.90	
		BIC	475.10	
		McFadden ρ^2	0.80	
		χ^2	3.51	
Distance level 3	0	V17: Maximum lateral acceleration of lane-changing (m/s2)	1.26***	0.20
		Random parameters (assumed to be normally distributed):		
		V4: Presence of TLV (presence = 1, absence = 0)	1.11***	0.37
		Standard deviation for the random parameter (V4)	0.47	0.15
		V5: Presence of TFV (presence = 1, absence = 0)	-1.10*	0.57
		Standard deviation for the random parameter (V5)	0.54	0.32
		V12: Lane-changing duration (s)	-0.11***	0.01
		Standard deviation for the random parameter (V14)	0.85**	0.35
	1	V14: Distance traveled during entire lane-changing process (m)	0.12***	0.04
		V16: Average lateral velocity of lane-changing (m/s)	-0.73***	0.39
		V20: 100 ＜ Lane-changing gap ≤ 150	0.93***	0.22
		Random parameters (assumed to be normally distributed):		
		V6: Longitudinal velocity of CLV at start of lane-changing (m/s)	0.89***	0.28
		Standard deviation for the random parameter (V6)	1.08***	0.32
		AIC	448.40	
		BIC	469.30	
		McFadden ρ^2	0.58	
		χ^2	3.78	

Notes: *, **, and *** denote the statistical significance at 0.1, 0.05 and 0.01 levels, respectively.

TABLE 5. The statistics of LCRM in different lane-changing scenarios.

Lane-changing scenarios	Mean	Std. Dev
Pattern 1 (TLV=1)	0.774	0.420
Pattern 2 (TLV=0)	0.889	0.316

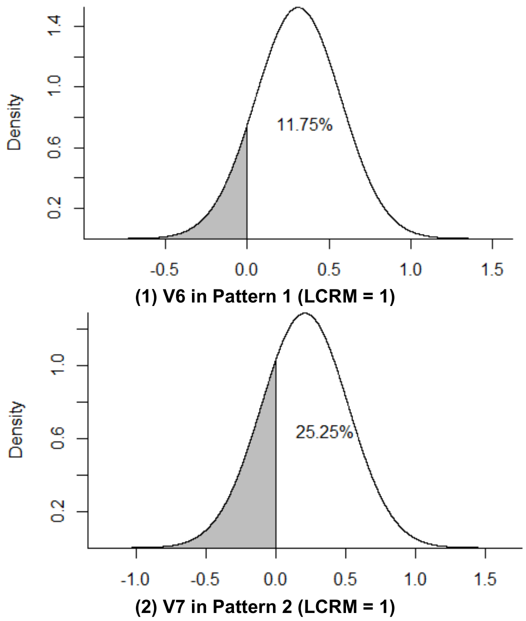

FIGURE 10. The probability density of random parameters in the models with heterogeneity in means.

TABLE 6. The average elasticity of V2 and V3 (disaggregated by lane-changing scenarios).

Variables	Average elasticity (%, in the case of LCRM=1)	
	Pattern 1	Pattern 2
V1: distance to tunnel entrance≤400 m*		
V2: 400 m<distance to tunnel entrance≤800 m	-0.86	-2.76
V3: 800 m<distance to tunnel entrance≤1200 m	-0.66	0.36

Note: * indicates that this variable is a benchmark variable.

92% in patterns 1 and 2, respectively. A study conducted by. Leeming [57] illustrated that the left side of the road is safer to drive on. Thus, the fact that the majority of vehicles change lanes to the left may indicate that some vehicles perform lane-changing in pursuit of a safer driving environment, but they ignore that such behaviour may be a contributing factor to risky lane-changing behaviour.

6.2 Distance level to tunnel entrance

TABLE 7 shows the statistics for the LCRM at different distance levels. Mean values of LCRM for the three distance levels, level 1 and 2, which are closer to the tunnel entrance, are higher than level 3, which is further away from the tunnel entrance, implying that vehicles are more likely to perform potentially risky lane-changing behaviour close to the tunnel entrance.

TABLE 7. The statistics of the LCRM at different distance levels to the tunnel entrance.

Distance level to tunnel entrance	Mean	Std. Dev
Level 1 (distance≤400 m)	0.895	0.310
Level 2 (400<distance≤800)	0.824	0.383
Level 3 (800<distance≤1200)	0.786	0.415

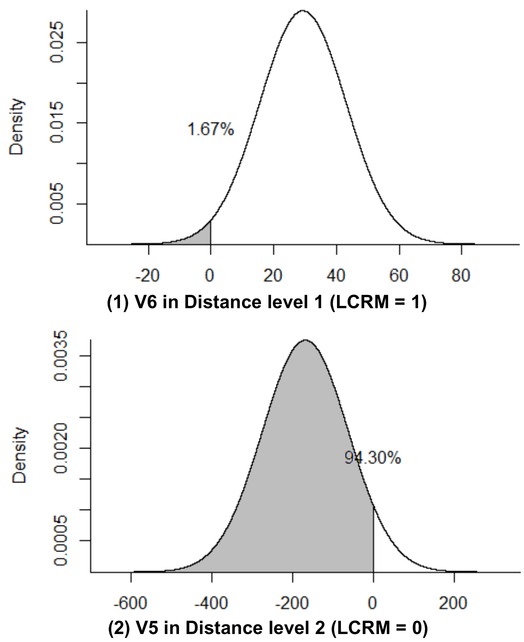

FIGURE 11. The probability density of random parameters in the models with heterogeneity in means.

TABLE 7 summarizes the results of parameter estimation of the mixed logit model of the three distance levels. This is analysed below in terms of the impact of different factors on the risk of lane-changing at different distance levels.

(1) The impact of vehicles in the current lane: In the current lane, we are mainly concerned with the driving status of the CLV. The effect of V6 (the longitudinal velocity of CLV at the start of lane-changing) on the risk of lane-changing is significant at all three distance levels. From the parameter estimation results, the longitudinal velocity of CLV is positively correlated with risky lane-changing. At distance level 1, V6 is set as a random parameter found to be heterogeneous, and its probability distribution is shown in FIGURE 11 (1). It can be concluded that with the increase in the longitudinal velocity of the CLV, the 1.67% probability of vehicles performing risky lane-changing is lower, and the 98.33% probability of vehicles doing the same is higher. In addition, at distance level 2, V7 (longitudinal distance to CLV at the start of lane-changing) also has a significant influence on the risk status of lane-changing. The greater the distance between SV and CLV is, the lower the probability of risky lane-changing, which is consistent with the above conclusion.

(2) The impact of vehicles in the target lane: Both the leading vehicle and the following vehicle in the target lane have significant influences on the risk of lane-changing. The average elasticity of V4 (presence of TLV) and V5 (presence of TFV) are summarized in TABLE 8.

TABLE 8. The average elasticity of V4 and V5 (disaggregated by distance level to tunnel entrance).

Variables	Average elasticity (%, in the case of LCRM=1)		
	Distance level 1	Distance level 2	Distance level 3
V4: Presence of TLV (presence = 1, absence = 0)	-0.55	0.22	-18.89
V5: Presence of TFV (presence = 1, absence = 0)	2.39	0.18	0.52

The presence of TLV has different effects on the risk of lane-changing at different distance levels. At distance level 1, the presence of TLV reduces the probability of risky lane-changing. At distance level 2, which is relatively far from the tunnel entrance, the situation is exactly the opposite, with the presence of TLV increasing the probability of risky lane-changing. By comparing the conclusions at distance levels 1 and 2, it suggests that in the absence of TLV, the possibility of performing risky lane-changing in the access zone is increased compared with that in the sections slightly farther from the tunnel entrance. The reason for this may be that drivers are willing to make risky lane changes to gain better forwards visibility conditions once inside the tunnel. At distance level 3, which is farther from the tunnel entrance, the presence of the TLV increases the probability of risky lane-changing, indicating that drivers in this area may consider the risk that the TLV may cause to lane-changing and choose to change lanes more carefully.

The effect of the presence of TLV on the risk of lane-changing is obvious, with the existence of TFV increasing the probability of risky lane-changing, regardless of the distance level. The risk increase probabilities from distance levels 1 to 3 are 2.39%, 0.18% and 0.52%, respectively. Furthermore, at distance level 2, V5 was found to be used as a random parameter with heterogeneity in the mean. Its probability distribution is shown in FIGURE 11 (2), which suggests that in contrast to the absence of TFV, 94.30% of vehicles are less likely to perform a safe lane change in the presence of TFV, and 5.7% do the exact opposite.

(3) The impact of SV: The average longitudinal velocity (V15), average lateral velocity (V16) and maximum lateral acceleration (V17) of SV all significantly affect the risk of lane-changing. According to the results of parameter estimation, the greater SV's average longitudinal velocity at distance level 2 is, the lower the probability of lane-changing at risk. Similarly, the average lateral velocity of SV is also negatively correlated with the probability of a risky lane-changing. Whether at distance level 2 or 3, the probability of risky lane-changing behaviour becomes greater as the maximum lateral acceleration of SV increases. However, at distance level 1, the average longitudinal velocity and average lateral velocity of the SV are positively correlated with the probability of risky lane-changing, which is different from distance levels 2 and 3.

(4) The impact of the lane-changing process: The lane-changing duration (V12) and the distance travelled during the entire lane-changing process (V14) are both reflections of the lane-changing process. For all distance levels, the longer the distance travelled during the entire lane-changing process is, the lower the probability of risky lane-changing. However, lane-changing duration is negatively related to the safety of lane changes at distance level 3 and positively correlated with safe lane changes at distance level 1. Therefore, in the access zone, a longer lane-changing duration and shorter distance travelled during the entire lane-changing process are more conducive to safety.

(5) The impact of the lane-changing gap: The lane-changing gap is also an influencing factor of risky lane-changing in certain situations. At distance level 2, V22 (lane-changing gap $>$ 200 m) has a significant impact on the risk of lane-changing. By calculating its average elasticity, it can be concluded that, compared with other cases, when the lane-changing gap is $>$200 m, the probability of performing risky lane-changing increases by 0.05% at distance level 2. Similarly, it can be learned that at distance level 3, when $100 <$ Lane-changing gap ≤ 150 (V20), the probability of performing risky lane-changing increases by 8.82% at distance level 3.

VI. CONCLUSION

This research mainly investigated the contributing factors of lane-changing safety from the perspective of different lane-changing scenarios, and analyzed the correlation between the distance to the tunnel entrance and the risk status of lane-changing. A naturalistic driving tests dataset was used to extract data on the lane-changing process as the basis for this study, and Lane-Changing Risk Margin (LCRM) was developed to assess the risk profile of vehicles changing lanes. Several mixed logit models are established in two patterns of lane-changing scenarios and three distance levels to tunnel entrance. The main findings of model parameter estimation can be summarized as follows:

(1) Compared with other parts of adjacent sections of tunnel entrance, the probability of risky lane-changing is generally slightly higher in the access zone connecting the tunnel entrance.

(2) The leading vehicle in the target lane (TLV) is an important factor contributing to the potential risk status of lane-changing.

In the presence of TLV, the risk of lane-changing was positively correlated with the longitudinal velocity of TLV, and negatively correlated with the distance between SV and TLV. Therefore, it is necessary to be vigilant that drivers ignoring the risks and making unsafe lane-changing when

TLV are travelling at higher speeds and the smaller longitudinal distance between SV and TLV.

In the absence of TLV, the probability of performing risky lane-changing increases in the access zone compared with that in the other parts of adjacent sections of tunnel entrance. It indicates that drivers may make risky lane changes to gain better forward visibility conditions once inside the tunnel.

(3) The following vehicle in the target lane (TFV) is a contributing factor. Compared to the absence of TFV, the probability of risky lane-changing in the presence of TFV is higher. In other words, the presence of TFV is detrimental to the safety of lane-changing.

(4) The leading vehicle in the current lane (CLV) also contributes to the risk status of lane-changing. Heterogeneity was found when the longitudinal velocity of CLV and the longitudinal distance between SV and CLV were set as random parameters, suggesting individual differences in the effect of CLV on the risk of lane-changing.

(5) According to the results of parameter estimation, the longer the lane-changing duration is, the higher the probability of safe lane-changing in all lane-changing scenarios. Similarly, the shorter the distance travelled during the entire lane-changing process is, the higher the probability of safe lane-changing at all distance levels. Therefore, to ensure the safety of lane-changing on the adjacent sections of the tunnel entrances, drivers may be advised to extend the lane-changing duration appropriately and complete the lane-changing process within a short distance as much as possible.

This research conducts a targeted study on the contributing factors of the risk status of lane-changing behaviour on adjacent sections of tunnel entrances, filling the gap in the field of refined research. However, there are still some issues that should be addressed in follow-up studies. The first is that this paper only analyzes lane change scenarios where surrounding vehicles are cars and does not explore the impact of different vehicle types on lane-changing risk on adjacent tunnel sections due to the naturalistic driving tests data collection limitations. In addition, as we assumed that the unobserved heterogeneity captured by random parameters is independent, the correlation among the distribution of random parameters in the model remains to be investigated.

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