Lane Changing in a Vehicle-to-Everything Environment

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Research on a Vehicle Lane-Changing Model in the Tunnel Area by Considering the Influence of Brightness and Noise Under a Vehicle-to-Everything Environment

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Digital Object Identifier 10.1109/MITS.2022.3197462
Date of current version: 6 September 2022

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***Abstract*—As there are many factors affecting vehicle lane changes in a tunnel, which leads to the unstable state of vehicles during lane changes and an increase of collision events, a new vehicle lane-changing model is proposed by considering the influence of typical factors such as noise and brightness in a tunnel under a vehicle-to-everything (V2X) environment. First, V2X-based technology enables real-time access to a target vehicle surrounding information characteristics in a tunnel, establishing a lane-changing decision model to quantify the willingness of vehicles to change lanes. Second, considering safety as a prerequisite for a lane change, establishing a vehicle safety lane-change-distance model and a minimum safe-distance model was introduced for comparison to evaluate the safety of lane changing. On this basis, considering the noise and brightness effects of a tunnel, the relationship between brightness, noise, and response time of human-driven vehicles, hybrid driving vehicles, and autonomous vehicles is quantitatively analyzed, and then a new vehicle lane-changing model in a tunnel is established. The results of the research show that brightness in a tunnel has a more significant effect on the driver than noise. At the same time, autonomous driving, as well as hybrid driving, has better stability and comfort with less change in velocity, acceleration, and other states during lane changing in a tunnel compared to manned driving, which proves the reasonableness of the model and helps to provide a model basis for research of real vehicle lane changing under a V2X environment.

With the rapid development of vehicle technology, it is difficult to rely on road infrastructure alone to solve increasingly prominent urban road traffic problems. From the perspective of intelligent transportation, the application of vehicle-to-everything (V2X) technology to roads can effectively relieve road pressure and solve traffic problems. Lane changing is one of the basic driving behaviors of vehicles on the road, and there is much research on lane changing of vehicles on the road. However, most of the simulation scenarios are studies of vehicle lane-change trajectories and decisions on motorways and urban roads, and the research on lane changing of vehicles in a tunnel is rare. The main reason for this is that the driving vehicles in a tunnel face a series of challenges, such as sightline, noise, and so on, and that many tunnels do not allow vehicles to change lanes. However, on 15 March 2019, the Xiang'an District tunnel in China allowed vehicles to lane-change in certain areas to increase tunnel capacity and alleviate road congestion.

Our work mainly studies a tunnel, that allows a vehicle to lane-change. As the tunnel environment requires certain driving conditions, Yeung et al. [1] researched how tunnel lighting impacts a driver's vision, and Amundsen and Ranes showed that tunnel-lighting conditions affect a driver's line of sight [2]. The environment inside the tunnel is relatively closed and not affected by natural weather factors. This, can cause the driver to feel depression psychology while driving, and the vehicle's exhaust emissions can affect the driver's visibility, and thus affect if the driver can accurately judge the information of the surrounding vehicles. Based on this, this article analyzes the track change of different driving types of vehicles in the tunnel under the V2X technology, reducing the influence of the tunnel environment on the driver's vision and psychology.

Vehicle lane-change studies have focused mainly on the lane-change model of trajectories of autonomous vehicles [3], [4], [5], [6], and the ways to increase the intelligence of autonomous vehicles [7], [8]. Few studies consider human-driven vehicles, autonomous vehicles, and hybrid vehicles in an integrated manner. In this article, a vehicle lane-changing model based on V2X technology is constructed and collects the surrounding information through vehicle communication in a V2X environment to decide the lane change. In addition, regular data such as position and velocity, as well as some data cannot be obtained directly, including acceleration, steering angle, and the mass of the vehicle, can be transmitted in real time between vehicle to vehicle (V2V) and vehicle to infrastructure (V2I).

The innovations of our work are as follows: 1) the lane-changing willingness of drivers is quantified through construction of the lane-changing decision model; 2) considering safety prerequisites in the tunnel area, a minimum safe-distance model is introduced for comparison to evaluate the safety of lane changing; and 3) analyzing the relationship of brightness, noise, and response time, a lane-changing model based on brightness and noise in the tunnel area is created.

Related Work

A polynomial trajectory curve was widely used for the lane-change trajectory curve. Shim et al. proposed a trajectory planning method based on a sixth-order polynomial, but there were many unknown coefficients [9]: the calculation was cumbersome and the convergence velocity was slow. In [10] and [11], the trajectory of lane changes based on a quintuplet polynomial was described. Zhang et al. used a cubic polynomial curve to construct a vehicle lane-changing trajectory [12] and Zhou et al. researched the lane-changing strategy by optimizing a cubic polynomial [13]. The polynomial ensures continuity of the trajectory and increases stability of the vehicle. A quintuplet polynomial has better continuity and comfort than cubic polynomials, and unknown parameters are less than seventh polynomials. On the basis of this, our work uses a quintuplet polynomial as the basis for describing the trajectory of the vehicle in the tunnel.

> Using communication equipment or V2X technology improves the information acquired from surrounding vehicles while weakening the information acquired through vision.

According to relevant research, the driver-fatigue effect is correlated with the noise in the environment [14]. Fatigue effects increase driver response time, and noise is indirectly related to driver response time [15]; thus, many scholars have conducted research on the related problems caused by noise in the environment. He et al. studied the influence of velocity characteristics and yaw angle of interior noise [16]. Li et al. studied the influence of aerodynamic noise and tire radiation noise on a vehicle at a high velocity [17]. Hu and Wang studied a driver-fatigue-detection system based on an electroencephalogram in a noisy environment [18]. Zhao analyzed the characteristics of noise and their influence in the tunnel area, and studied their active prevention and control measures to achieve improved hearing [19]. When the vehicle changes lanes in the tunnel area, the driver's response time will greatly affect driving safety. As discussed in the aforementioned literature, the existing research on the impact of noise in tunnel areas is not in depth enough, and there are relatively few studies that consider the influence of noise on lane changes in tunnel-driving conditions.

Wang et al. [20] indicated that crashes were more likely to occur when a vehicle moves from bright to dark environments, known as the *black hole effect*. It is necessary to analyze the influence of tunnel lighting on a driver's sight of the line. During tunnel operation, a driver's sight will follow the lighted environment to change while maintaining a high degree of attention. Research has shown that human vision during driving will cause stress and fatigue due to excessive attention [21]. He et al. researched the spatial distribution of how lighting environment parameters significantly influence one's visual performance, but refer to LED brightness for analysis [22]. They mainly analyzed the influence of different lighting environments in a tunnel on drivers' vision and show how lighting can make a more stable environment with higher sidewall brightness, according to pupil changes and eye movement parameters [23]. Through these works, this article quantitatively analyzes the impact of tunnel brightness on a driver's vision.

In general, realistic lane-changing behavior contains two stages: lane-changing decision and lane-changing implementation. Nilsson et al. divided the lane-changing algorithm into three parts [24]: decision-making, execution, and adjustment periods, which can generate a safe and stable trajectory during lane changing. Based on one's driving style during lane changing, the lane-change trajectory planning of a driver's style was studied through classification [25], but this research has not combined the information from V2V or V2I communication, nor is it timely and flexibly applied. Using communication equipment or V2X technology improves the information acquired from surrounding vehicles while weakening the information acquired through vision.

However, these works showed that the polynomial trajectory curve has been used by most scholars and experts to study the lane-change trajectory of vehicles on urban roads. In the tunnel-area scenario, vehicles are often not allowed to change lanes due to special traffic characteristics. But in many cases, there are many aggressive drivers who change lanes in the tunnel area and the decision to change lanes is often highly subjective; their lane-change behavior is often performed when the intention to change lanes is not detected and the conditions for a safe lane change are not available. The existing studies that quantitatively analyze drivers' lane-change decision behavior and safety preconditions in tunnels are not comprehensive. At the same time, there are also many factors affecting drivers' in a tunnel area. These factors somehow indirectly contribute to the occurrence of traffic accidents [26], [27]. Many of the factors are also analyzed qualitatively and experiments data in the existing studies, fewer studies have quantified the relationship among these factors and the actual degree of impact on the vehicle during travel. Therefore, there are also relatively few studies on vehicle lane-changing behavior by considering the factors affecting vehicle lane-changing behavior in a tunnel area. The research on the vehicle lane- changing process in a tunnel area is not comprehensive, has hidden dangers, and needs to be further studied.

According to the reviewed literature, polynomials are widely used in vehicle lane-changing, but they are studied for a single vehicle, and different types of vehicles are rarely combined. Vehicles driving in tunnels are severely

In the tunnel area relative to the urban road, the space is relatively closed, the noise is also high, and the driver's response is usually a perceptual-behavioral process caused by external factors.

impacted by tunnel brightness and noise. Although it is possible to analyze qualitatively how a tunnel's lighting material and spatial features affect a vehicle driver's vision and hearing, there are few quantitative analyses of the effects of brightness and noise on a driver's response time. Our work is based on polynomial lane changing, and a new lane-changing model is established in the tunnel by taking into account a vehicle's lane-changing intention and safe lane-changing conditions, adding different influencing factors, analyzing the state changes during vehicle lane changing under the influence of these conditions, and deciding whether the lane-changing model is appropriate.

Methodology

According to the characteristics of the tunnel area and the technical characteristics of V2X, this article quantitatively analyzes a driver's lane-changing-decision intention and the premise of a safe lane change, and the extent to which the brightness and noise of the tunnel area affect the driver's lane change are quantified through the driver's lane-change-response time. It then proposes a lane-changing model by considering tunnel brightness and noise on the V2X environment. Therefore, the model is primarily composed of the following three modules:

1) decision model for vehicle lane changing
2) safety-evaluation model based on safety distance
3) vehicle lane-changing model considering noise and brightness effects.

Decision Model for Lane Changing

In general, realistic lane-changing behavior contains two stages: lane-changing decision making and lane-changing implementation. According to the information available, vehicles in the Xiang'an District tunnel may be diverted to increase road capacity. However, a vehicle lane change is not allowed in the tunnel and can only occur within specified intervals. Some tunnels can only be at the exit according to the destination lane change, and may also be called a *mandatory lane change*.

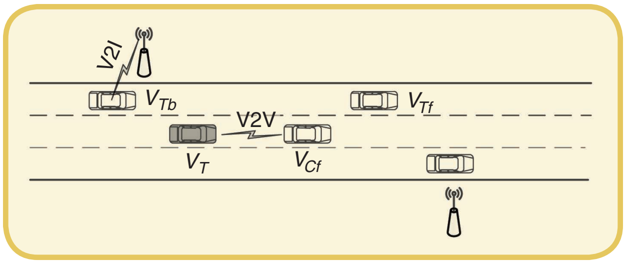

FIG 1 A diagram of a lane change. V2I: vehicle to infrastructure; V2V: vehicle to everything.

In this article, V2X technology is used to transmit information around the vehicle and the situation in the tunnel to the adjacent vehicles, and then to determine whether to change lanes. The process is depicted in Figure 1. Therefore, to quantitatively describe the driver's lane-change decision intention and define velocity advantages and disadvantages, when the speed of lane-changing vehicles reaches the following three conditions at the same time, it means that the lane-changing vehicles have the velocity advantages of

1) the velocity of the target vehicle in the current lane is less than the velocity of the vehicle in front of the current lane.
2) the velocity of the target vehicle in the current lane is greater than the velocity of the vehicle behind the target lane.
3) the current lane target vehicle's velocity is less than the target vehicle's front velocity.

In addition to the aforementioned conditions, it shows that the speed of the lane-change vehicle is at a disadvantage. Therefore, the following lane-change decision model is constructed:

$$S_1 = V_T - V_{Cf} \tag{1}$$

$$S_2 = V_T - V_{Tf} \tag{2}$$

$$S_3 = V_T - V_{Tb} \tag{3}$$

$$\begin{cases} S_1 < 0, S_2 < 0, S_3 > 0 & \text{velocity advantage} \\ \text{others} & \text{velocity disadvantage,} \end{cases} \tag{4}$$

where, S_i is the velocity difference between the two vehicles, V_T is the target vehicle's velocity, V_{Cf} is the velocity of the vehicle ahead in the current lane, V_{Tf} is the velocity of the vehicle ahead in the target lane, and V_{Tb} is velocity of vehicles behind in the target lane.

Safety-Evaluation Model Based on Safety Distance

The vehicle can change lanes on the condition that it avoids a collision with the vehicle in front of the target lane and the vehicle behind the target lane. When a human-driven vehicle detects a situation, it automatically extends the safe distance between the front and back of the vehicle, while the automatic driving vehicle analyzes the data collected from the surrounding environment to determine the appropriate safe distance between the vehicles. As shown in Figure 2, the safe distance between lane-changing vehicle a and vehicle b is L_1, and the safe distance between lane-changing vehicle a and vehicle c is L_2. When the vehicle is in the $(X_1 - X_3, X_2 - X_1)$ zone, it is safe for the vehicle to reach the target lane; in other words, there are no collisions with the front and rear cars.

This article builds the safety-evaluation model during a vehicle's lane-change process in the tunnel area based on the required safety-distance conditions and the introduction of the minimum safety-distance model. Here, the specific establishment process is presented.

According to vehicle kinematics, the displacement of vehicle a during a lane change is

$$X_a = \int_{t_1}^{t_2} (v_a + a_a t)dt \tag{5}$$

The lane-changing lateral displacement of vehicle a in time t is

$$X_{ax} = \int_{t_1}^{t_2} \cos\theta(t) * (v_a + a_a t)dt \tag{6}$$

The longitudinal displacement X_{ay} is

$$X_{ay} = \int_{t_1}^{t_2} \sin\theta(t) * (v_a + a_a t)dt \tag{7}$$

The driving displacement of vehicle b in the target lane is

$$X_b = \int_{t_1}^{t_2} (v_b + a_b t)dt \tag{8}$$

$$L(t) = \left| \int_{t_1}^{t_2} \cos\theta(t)(v_a + a_a t)dt - \int_{t_1}^{t_2} (v_b + a_b t)dt \right|, \tag{9}$$

where v_a and a_a are the velocity and acceleration, respectively, of the vehicle; a, v_b, and a_b are the velocity and acceleration of the vehicle; b, t_1, and t_2 are the start and end times of the lane change; and $L(t)$ is the distance of vehicles a and b.

Therefore, considering a wide range of safe distances, Kui et al. [28] introduced a revised function, establishing the safety-evaluation function

$$S_{\min} = 0.05896v(t) + 0.00451[v(t)] + 3 \tag{10}$$

$$L_s(t) = \begin{cases} \dfrac{L(t)}{S_{\min}} & L(t) < S_{\min} \\ 1 & L(t) \geq S_{\min}, \end{cases} \tag{11}$$

where $L_s(t)$ is the safety-evaluation function, $S_{\min}$ is the minimum safe distance, $L(t)$ is calculated by (9), and $v(t)$ is the velocity of the target vehicle.

The minimum safe distance between the target vehicle and the vehicle in front of the target lane is L_{s1}, and the minimum safe distance between the target vehicle and the vehicle behind the target lane is L_{s2}. Therefore, the minimum interval is $L_{s1} + L_{s2}$ between the lane change and the target lane.

As presented in Figure 3, a collision behavior during a vehicle lane changing needs to be solved by the lateral motion of the target vehicle. Therefore, this article analyzes the distance variation when a critical collision occurs between the vehicle from the current lane to the target lane by (12)

$$\begin{cases} y(t_1) + \dfrac{M}{2}\cos(\theta(t_1)) + \dfrac{B_1}{2}\sin(\theta(t_1)) = y_2 - \dfrac{B_2}{2} \\ y(t_2) - \dfrac{M}{2}\cos(\theta(t_1)) + \dfrac{B_1}{2}\sin(\theta(t_1)) = y_3 - \dfrac{B_3}{2}, \end{cases} \tag{12}$$

where y is the longitudinal coordinate value of vehicle a, y_2 is the longitudinal coordinate value of vehicle b, y_3 is the longitudinal coordinate value of vehicle c, M is the width of the target vehicle, $\theta(t_1)$ is the yaw angle of the target vehicle at the time of the collision, B_1 is the length of the target vehicle a, B_2 is the length of the vehicle b, and B_3 is the length of the vehicle c.

Influence of Noise on Response Time of Lane Changing in the Tunnel Area

In the tunnel area relative to the urban road, the space is relatively closed, the noise is also high, and the driver's response is usually a perceptual-behavioral process caused by external factors. Therefore, the noise in the tunnel area can easily affect the driver's response time. According to [29], when the vehicle's velocity in the tunnel area reaches 40–80 km/h, the *LPA dB* in the tunnel area can reach 75–89 dBA. At the same time, we

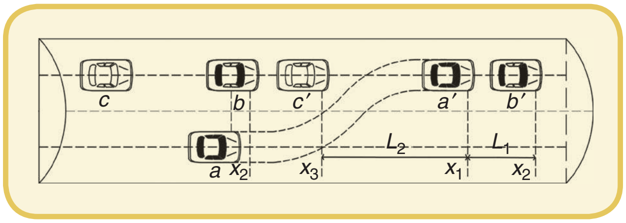

FIG 2 The minimum safety clearance for vehicle lane changing.

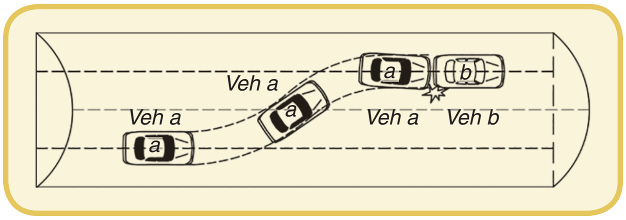

FIG 3 A collision diagram of the lane change of a vehicle.

know from the research experiment in [30] that noise in the tunnel area seriously affects the response time of drivers in the tunnel area. In these studies, the curve of the relationship between *LPA dB* and response time was fitted according to the experimental data, as illustrated in Figure 4.

Therefore, this article describes the relationship between *LPA dB* in the tunnel area and driver response time according to an approximate formula (13)

$$t_{\text{response}2} = k_1 \sin(k_2 \times (LPA\ dB) + k_3), \tag{13}$$

where $t_{\text{response}2}$ indicates the driver's response time, and k_1, k_2, and k_3 indicate the constant.

Influence of Brightness on Response Time of Lane Changing in the Tunnel Area

Tunnel brightness is quite important to ensure eye comfort and safety for drivers. In [31], the driver's response varies for different brightness levels when a vehicle is driving in the tunnel. According to [32], the relationship between brightness of the tunnel area and the driver's response is fitted by a polynomial, and a quantitative expression for the relationship is also obtained. The fitting results are shown in Figure 5.

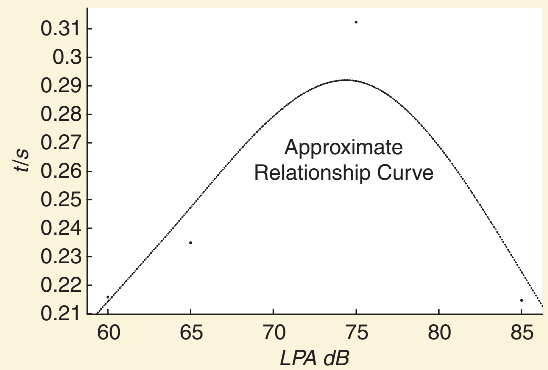

FIG 4 The curve of the *LPA dB* and the response time.

Therefore, this article quantifies the relationship between brightness and response time in the tunnel area through (14) as to describe the influence of brightness in the tunnel area on the vehicle in the driver's lane-change process

$$t_{\text{response}1} = -0.001525L^3 + 0.02726L^2 - 0.1707L + 1.044, \tag{14}$$

where $t_{\text{response}1}$ is response time (s), and L is background brightness (cd/m^2).

The fitting process is shown in Figure 5. With the increase of brightness, the response time decreases, that is, the driver's response time slows down as the tunnel brightness increases. As illustrated in Figure 5, there is a negative correlation between response time and brightness. However, there are some limitations between them, such as velocity of the data collection range of 40–80 km/h.

As presented in Figure 5, the brightness of different stages affects efficiency of the driver's response time differently. However, in the V2X environment, the vehicle can obtain the information of the vehicle ahead of time and make timely decisions, which can effectively reduce the response time of the driver in the tunnel area. As a result, research according to the different efficiency of illumination intensity defines three types driving, namely, manned, hybrid, and automatic driving (see Figure 6), and quantifies the relationship by establishing (15)

$$t_{\text{response}1} = \begin{cases} 0.68 \le t_{\text{response}1} < 1.04 & \text{Manned driving} \\ 0.66 \le t_{\text{response}1} < 0.68 & \text{Hybrid driving} \\ 0 \le t_{\text{response}1} < 0.66 & \text{Automate driving} \end{cases}. \tag{15}$$

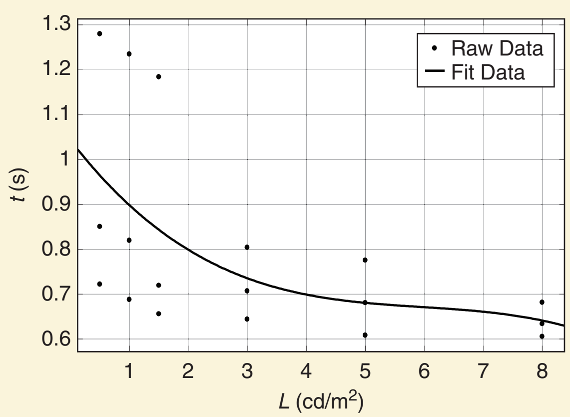

FIG 5 The fitting graph of the response time with background brightness.

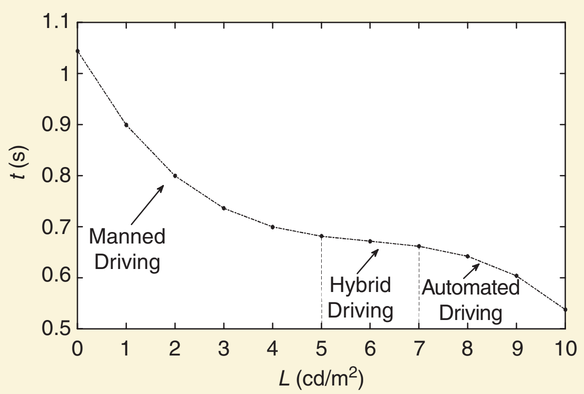

FIG 6 The response time of drivers under different driving types in a tunnel area.

Considering the Influence of Brightness and Noise for the Vehicle Lane-Changing Model in the Tunnel Area

First, to express the comprehensive influence of brightness and noise in the tunnel area on driver response time, propose the comprehensive response time model, as shown in (16)

$$t_{\text{response}} = \omega t_{\text{response}1} + (1-\omega)t_{\text{response}2} \quad 0 < \omega < 1 \tag{16}$$

where t_{response} indicates the comprehensive response time of vehicle lane change, and ω indicates the relative weight.

Then, Figure 7 shows the lateral and longitudinal change of the vehicle track-changing polynomial, where v is the velocity of the target vehicle, and θ is the angle between the directions of the target vehicle, which can be called the *heading angle*. The continuity and smoothness of the polynomial lane change in the vehicle lane-change trajectory model can effectively guarantee the comfort of the vehicle.

Finally, according to the characteristics of V2X technology, the lane-changing vehicle can obtain vehicle and position information about itself and the surrounding vehicles in real time to improve driving safety and lane-changing efficiency. To improve authenticity and objectivity of the lane-changing model, a part of the I-80 real data in next-generation simulation (NGSIM) is selected for fitting analysis, including speed, acceleration, and travel time, and the results are displayed in Figure 8.

Therefore, (17) is used as the basic track model of the tunnel area in this article

$$\begin{cases} x(t) = \sum\limits_{i=0} ai * t^i \\ y(t) = \sum\limits_{i=0} bi * t^i \end{cases} \quad 0 \le i \le 5, \tag{17}$$

where (a_i, b_i) is the polynomial coefficient of the quintuplet polynomial vehicle lane-changing mode, and t is the time of lane changing.

Suppose the starting position coordinates are (0,0) and the ending position is (x_1, y_1), the starting acceleration is zero and the ending acceleration is $(\ddot{x}_1, \ddot{y}_1)$, the heading angle of the initial position and the ending heading angle of the vehicle is zero. Therefore, the longitudinal and lateral equations of the beginning and end points are expressed by a matrix, as shown in (18)

$$X = \begin{bmatrix} x_0 \\ \dot{x}_0 \\ \ddot{x}_0 \\ x_1 \\ \dot{x}_1 \\ \ddot{x}_1 \end{bmatrix} = \begin{bmatrix} t_0^5 & t_0^4 & t_0^3 & t_0^2 & t_0 & 1 \\ 5t_0^4 & 4t_0^3 & 3t_0^2 & 2t_0 & 1 & 0 \\ 20t_0^3 & 12t_0^2 & 6t_0 & 2 & 0 & 0 \\ t_1^5 & t_1^4 & t_1^3 & t_1^2 & t_1 & 1 \\ 5t_1^4 & 4t_1^3 & 3t_1^2 & 2t_1 & 1 & 0 \\ 20t_1^3 & 12t_1^2 & 6t_1 & 2 & 0 & 0 \end{bmatrix} \begin{bmatrix} a_5 \\ a_4 \\ a_3 \\ a_2 \\ a_1 \\ a_0 \end{bmatrix} = \mathrm{T} \times A$$

$$Y = \begin{bmatrix} y_0 \\ \dot{y}_0 \\ \ddot{y}_0 \\ y_1 \\ \dot{y}_1 \\ \ddot{y}_1 \end{bmatrix} = \begin{bmatrix} t_0^5 & t_0^4 & t_0^3 & t_0^2 & t_0 & 1 \\ 5t_0^4 & 4t_0^3 & 3t_0^2 & 2t_0 & 1 & 0 \\ 20t_0^3 & 12t_0^2 & 6t_0 & 2 & 0 & 0 \\ t_1^5 & t_1^4 & t_1^3 & t_1^2 & t_1 & 1 \\ 5t_1^4 & 4t_1^3 & 3t_1^2 & 2t_1 & 1 & 0 \\ 20t_1^3 & 12t_1^2 & 6t_1 & 2 & 0 & 0 \end{bmatrix} \begin{bmatrix} b_5 \\ b_4 \\ b_3 \\ b_2 \\ b_1 \\ b_0 \end{bmatrix} = \mathrm{T} \times B. \tag{18}$$

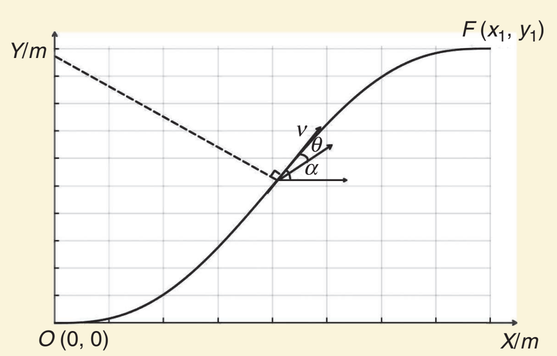

FIG 7 The vehicle trajectory diagram.

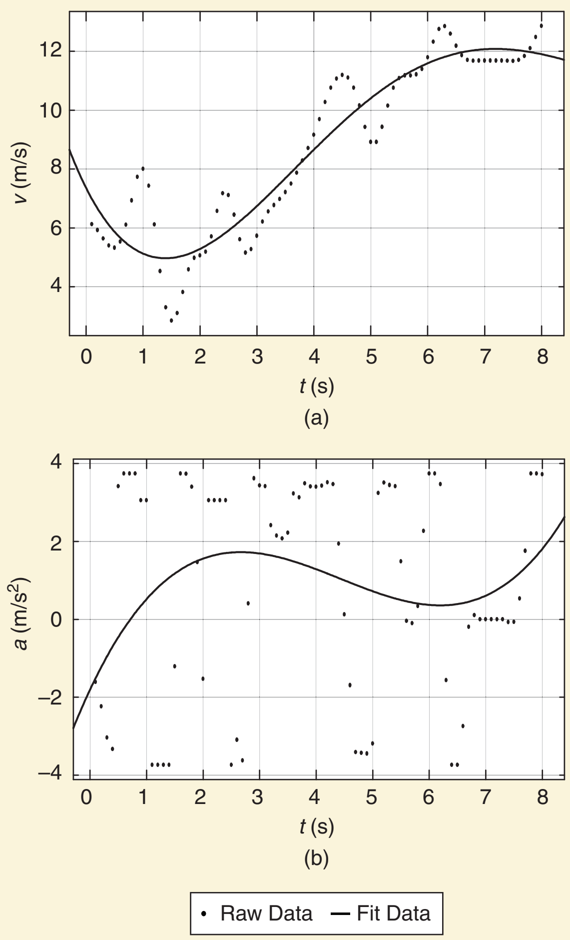

FIG 8 The I-80 partial data-fitting diagram. (a) A velocity change fitting and (b) an acceleration change fitting.

It is known from previous research that there is a delay in information transfer under a V2X environment.

Simulation and Analysis

The proposed lane-changing model is evaluated using a semiphysical traffic simulation. The typical lane-change scenarios from the real-world lane change data (NGSIM) and the driving trajectory is used for the base trajectory of the lane change model in the tunnel area, considering the effects of brightness and noise proposed in the article. Meanwhile, the simulations based on a MATLAB tool and a human-loop platform are performed on the proposed lane-changing model. Furthermore, experiments are conducted to verify driving-trajectory changes under the influence of noise and brightness of the three driving types and their differences.

It is known from previous research that there is a delay in information transfer under a V2X environment. As a result, a new lattice model [33] was constructed and implied that the delayed time effect contributes to restraining traffic jams in a two-lane lattice model. Assuming that the information transmission was credible, the established end-to-end model can reduce the communication delay to less than 20 ms [34], which reduced the information transmission delay time. That is, the response time of the driver and the track-generation time of the self-driving vehicle were reduced.

Simulation Introduction and Parameter Settings

Lane-changing data from an NGSIM are used to verify effectiveness of the proposed model by a human-in-the-loop platform. The NGSIM project used videos to capture real-world traffic information, including vehicle velocity, position, acceleration, and so on. As high-resolution, real-world vehicle trajectory data, NGSIMs are widely used to explore characteristics of the lane-changing process and calibrate and validate lane-changing models. For more data applications and detailed descriptions, the interested reader is referred to [35], [36], [37], [38], [39]. In this article, NGSIM data provide a lane-change environment for

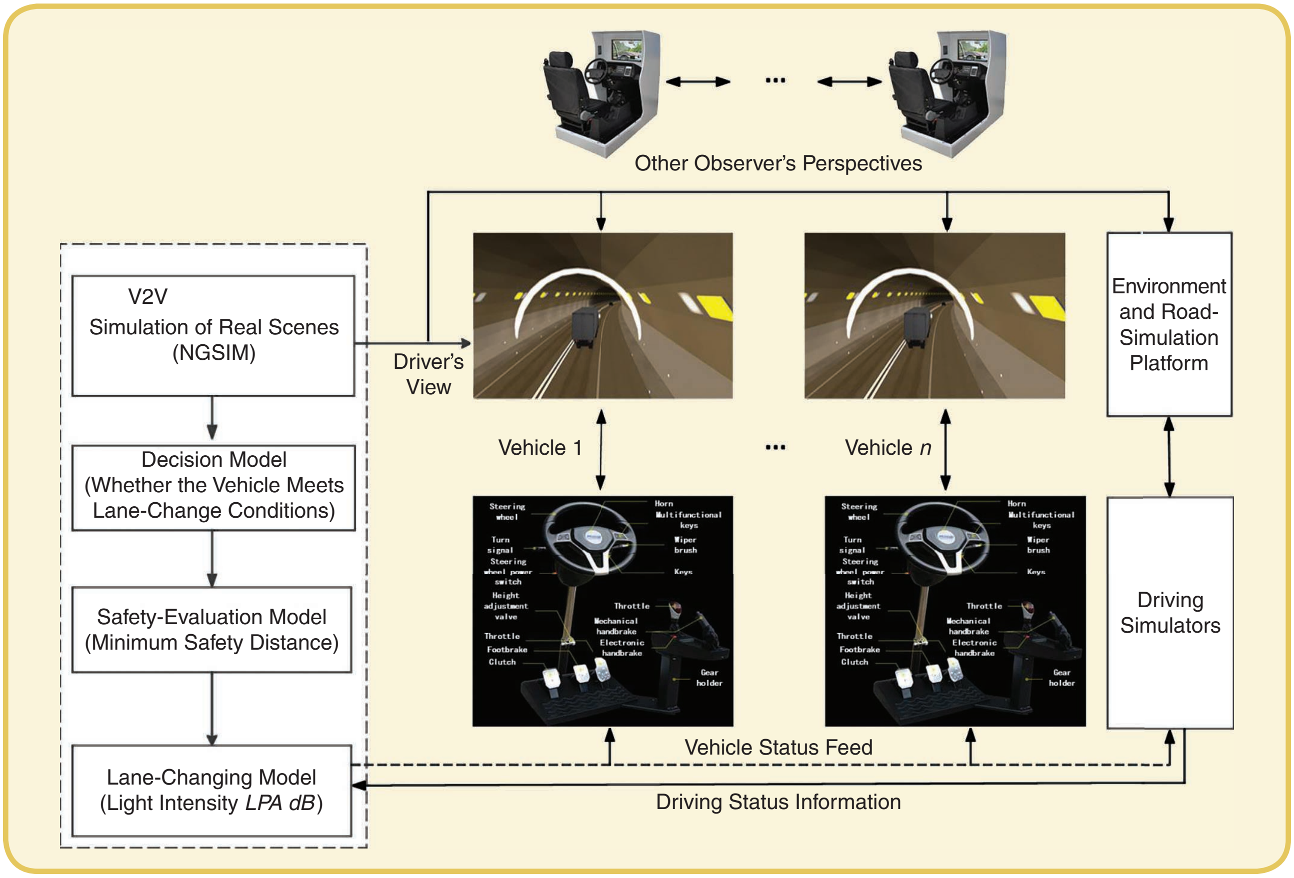

FIG 9 A semiphysical simulation flowchart of the lane-changing model in the tunnel area.

different types of vehicles. The human-loop simulation platform, combined with NGSIM data, is used to simulate the scenarios required for validation of the vehicle's lane-change model proposed in this article that considers the effects of brightness and noise, and to study the relative magnitude of the effects of noise and brightness on vehicle lane changing. The dynamic vision of a manned vehicle driving in the tunnel is related to the degree of brightness of the tunnel.

> Tunnel brightness and noise affect a driver's response time to lane-change by influencing a driver's visual and auditory perception.

Equation (14) shows that when there is low luminosity, the response time of the human eye is greatly affected. As the brightness increases, the response time of the human eye improves. The tunnel limits the velocity of the vehicle, and the brightness is constantly adjusted to achieve the appropriate state for the driver. However, during the actual driving process, the driver's visual data needs to be collected by a professional eye tracker. During the experiment, the driving time and visual distance of the lane-changing vehicle were adjusted to reflect the influence of vision during the vehicle lane-changing. Hybrid driving uses a ratio of 0.8 for automatic driving and human-driven vehicles for the simulation [40]. Therefore, it is necessary to further simulate the vehicle-state changes of manual, hybrid, and automatic driving under the influence of brightness intensity in a tunnel-area scenario to study the specific experimental procedure depicted in Figure 9.

Vehicle driving in a tunnel affects a driver's vision. For example, research [41] has indicated that a driver's sensory organs perceive traffic information as follows: vision accounts for 80% of the total, hearing 14%, and touch, taste, and smell each make up 2%; so vision was the main factor affecting the driver in the tunnel. Therefore, to complete the experiment and achieve the expected results, the simulation experiment of the vehicle's lane change made the following assumptions [42]:

- The initial lateral acceleration, lateral velocity, and lateral displacement of the target vehicle are all zero at the starting point of a lane change.
- The front and rear vehicles of the target vehicle and the front and rear vehicles of the target lane are the same in size and performance.
- The parameter setting assumptions are listed in Table 1.

Simulation Results and Analysis

Tunnel brightness and noise affect a driver's response time to lane-change by influencing a driver's visual and auditory perception. Many factors impact a driver's response time, which is also difficult to judge. In [43] and [44], the response time of the system has a significant impact on the safety of lane changes. Therefore, this article first simulates the proposed safety lane-changing model and then evaluates the safety of the lane-changing process in the work. Figure 10 presents the end result.

Figure 10 reflects the change of safety factors in the process of a vehicle's lane change. As shown in Figure 10, the safety factor is low at the beginning of vehicle's lane change and becomes higher as the lane-change time goes on, which conforms to the real lane-change process of vehicles and proves the effectiveness of the vehicle lane-changing model based on safe distance.

At the same time, brightness and noise in the tunnel area have different effects on vehicle lane changing. Therefore, to study the influence of noise and brightness

Table 1. Parameter settings of the vehicle lane-change simulation experiment.

Parameters	Parameter Settings
Curvature boundary conditions	$K(0)=K(x_i)=0, \frac{dK}{dx}(0)=\frac{dK}{dx}(x_i)=0$
Boundary conditions for single-valued functions	$y(0)=0,\ y(x_1)=y_1$ $\theta(0)=\dot{\theta}(0)=\theta(x_1)=\dot{\theta}(x_1)=0$
Boundary conditions with time as a parameter variable	$x(0)=y(0)=\dot{y}(0)=\dot{y}(t_1)=0;$ $x(t_1)=x_1 y(t_1)=y_1$
Driver response time (s)	t_{max}
a_i	$a_0=0, a_1=v_0, a_2=0, a_3=\frac{10x_1-6v_0t_1-4v_1t_1}{t_1^3}$ $a_4=\frac{-15x_1+7v_1t_1+8v_0t_1}{t_1^4}, a_5=\frac{6x_1-3v_1t_1-3v_0t_1}{t_1^5}$
b_i	$b_0=0, b_1=0, b_2=0, b_3=\frac{4y_1}{t_1^3}$ $b_4=-\frac{15y_1}{t_1^4}, b_5=\frac{6y_1}{t_1^5}$
Vision, hearing, touch, taste, smell (%)	80, 14, 2, 2, 2

on vehicle lane changing in tunnel area, in this article, the state changes of manual driving in lane changes process under the weights of $\omega = 0.5$, $\omega = 0.6$, and $\omega = 0.7$ are simulated.

Figure 11(a) shows a simulation diagram of the acceleration state changing with time under the various weights, while Figure 11(b) depicts a simulation diagram of the longitudinal velocity state changing with time. It can be seen that as the weight of brightness in the tunnel area increases, the longitudinal velocity and acceleration state become more visible. This indicates that that when vehicles change lanes in the tunnel area, brightness has a greater impact on lane changes than does noise.

Brightness in the tunnel has a greater influence on the driver's lane changing. Therefore, based on the safe lane-change model, numerical simulation experiments were carried out further on the lane-changing model of vehicles proposed in this article, and the characteristics of lateral distance, longitudinal distance, lateral velocity, longitudinal velocity, and acceleration of three different types of vehicles driven by manned, hybrid, and automatic driving, respectively, are compared. The results are presented in Figure 12(a)–(e).

Figure 12(a) and (b) shows changes in the lateral and longitudinal distances, respectively, of the three different types of vehicles. When vehicles change lanes, the brightness in the tunnel area has little effect on the lateral distance, the response of manned driving vehicles is slower, and the lane-change completion time is longer. Figure 12(c) and (e) depicts changes in the lateral and longitudinal velocity, respectively, of three different types of vehicles. It can be seen that, regardless of longitudinal and lateral velocity, the change rate of automatic driving is smaller and more stable than that of hybrid and human driving. Meanwhile, Figure 12(d) illustrates the acceleration changes of manned, hybrid, and autonomous driving vehicles in the process of the lane change. It can be seen that vehicles of all three driving types are decelerating during the lane-change process, with the velocity changes of manned driving being the most pronounced.

As shown in the aforementioned simulation results, there are many factors affecting the lane-changing behavior of drivers in the tunnel area, which is frequently manifested in the driver's lane-change response time. This article focuses on the effects of brightness and noise levels in the tunnel area. Because brightness generally affects the driver's field of vision, its impact is much greater, as demonstrated by the research. Meanwhile, this also can be seen from an analysis of the changes in the lateral distance, longitudinal distance, lateral velocity, longitudinal velocity, and acceleration of manned, hybrid, and automatic driving. Brightness has less of an influence on an autonomous vehicle in the tunnel area during the lane-change process, the velocity change of the manned driving vehicle is greater, and the lane-change response is significantly slower than that of the autonomous vehicle and hybrid driving, which is not conducive to the comfort and safety of driving in the tunnel area.

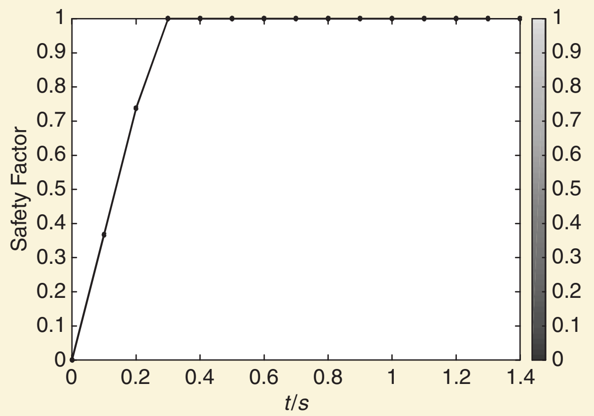

FIG 10 A safety evaluation of vehicle lane-change processes.

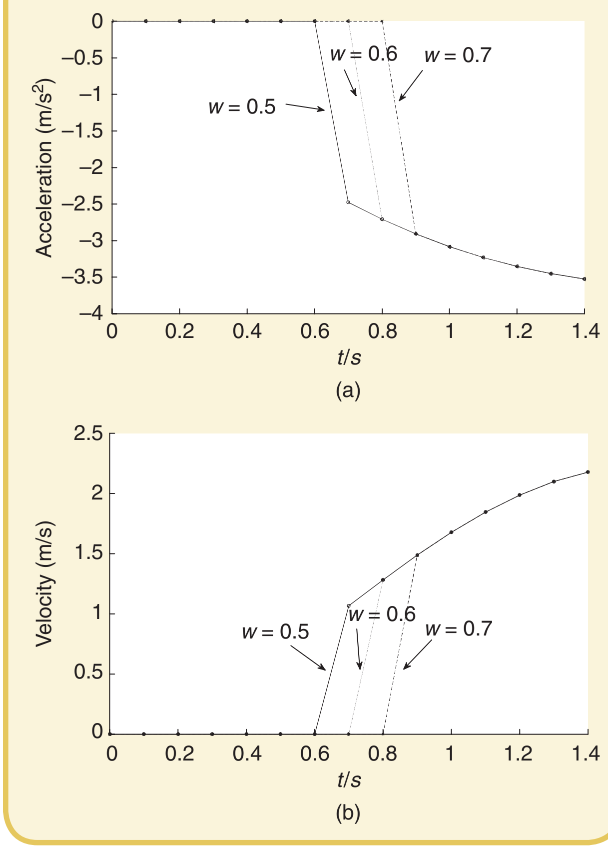

FIG 11 The velocity and acceleration changes of manned driving vehicles during lane changes under different weights. (a) Acceleration changes during lane changes of vehicles under different weights. (b) Longitudinal velocity changes during lane changes of vehicles under different weights.

Conclusion

In this article, the tunnel area in the V2X environment serves as the research scenario. First, the willingness of vehicles to change lanes is quantified by building a vehicle lane-changing decision model. Second, the safety of vehicles during lane changes is quantified by building a vehicle safety-evaluation model based on vehicle safety spacing. On this basis, the relative influence of brightness

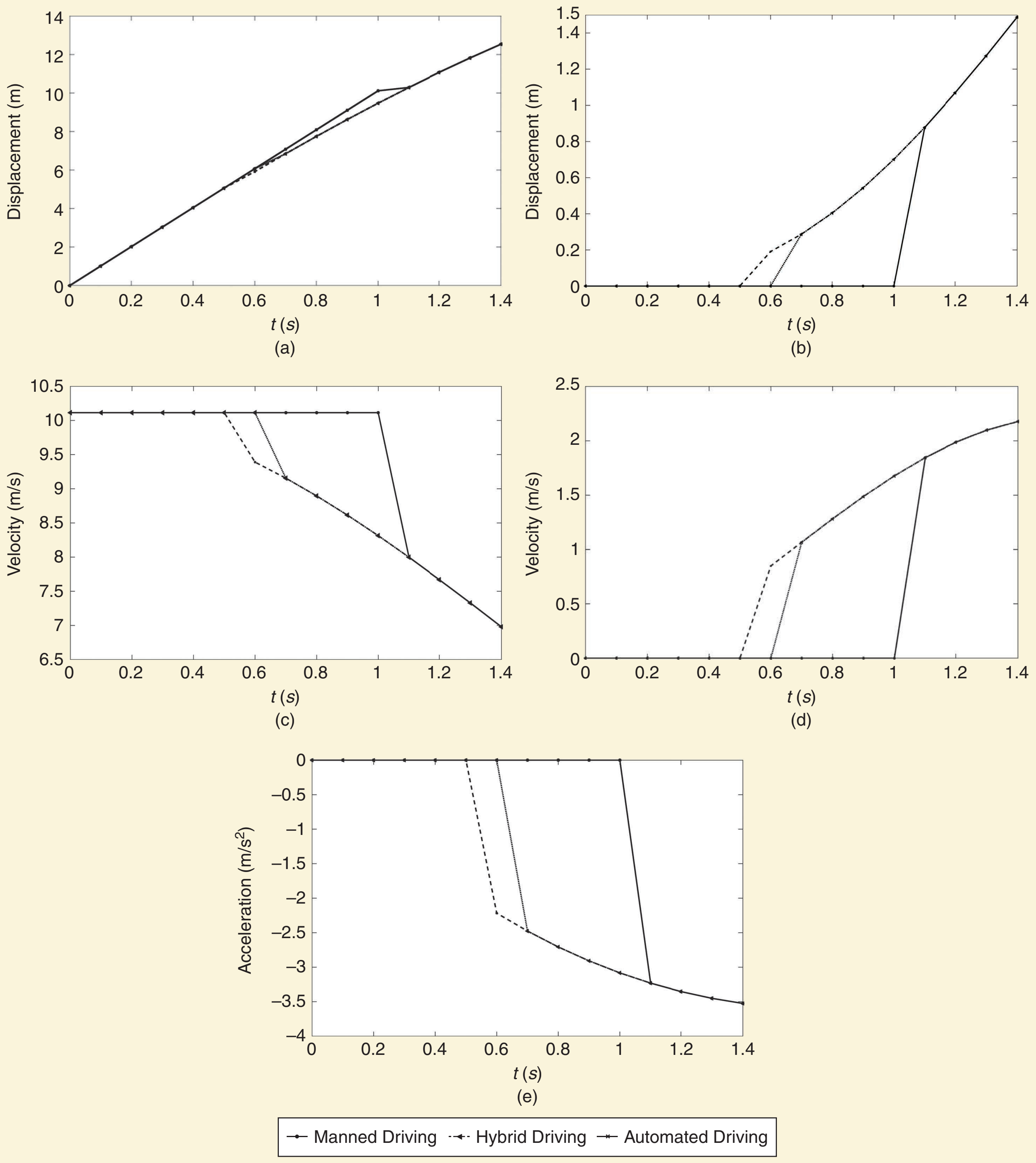

FIG 12 The state changes of three different types of vehicles. (a) The change in lateral distance, (b) change in longitudinal distance, (c) change in the lateral velocity, (d) change in longitudinal velocity, and (e) change in the lateral velocity of vehicles changing lanes.

and noise on lane changing in the tunnel area is analyzed, a new vehicle lane-changing model in the tunnel area is established, and the vehicle's lane-changing process in the tunnel area is studied. The results of the research assess the safety of lane changing in the tunnel area and compare the relative magnitude of the influence of brightness and noise on the driver's lane-changing behavior in the tunnel area. The results also analyze variation in safety, distance, velocity, acceleration, and other characteristics of manned, hybrid, and autonomous driving under the influence of brightness during lane changing in the tunnel area. This increases assurance of safe driving in the tunnel area, helps improve driving comfort in the tunnel area, and serves as a model for future lane-changing tests of manned, hybrid, and autonomous driving in the V2X environment.

Autonomous driving vehicles will play an important role in addressing urban traffic issues. Although automation will not happen overnight, we will be commuting in self-driving cars one day. Prior to this, hybrid driving vehicles served as a bridge between human-driven vehicles and autonomous driving vehicles. Therefore, in the future, we will concentrate on investigating the characteristics of hybrid driving trajectory transformation in various scene areas at the same time the different influencing factors are considered to provide theoretical references for subsequent research on autonomous driving.

Acknowledgment

This work was supported by the Guangxi Key Research and Development Projects (Guike AB21220052), the Guangxi Science and Technology Major Project (Guike AA22068101), the Major Project of Liuzhou City (2021CAA0101), the Guilin Innovation Platform and Talent Plan Project (20210217-15), the Guangxi Key Laboratory of Trusted Software (kx202023), the National Natural Science Foundation of China (52072214), and the Innovation Project of Guilin University of Electronic Technology Graduate Education (2021YCXS178).

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References

[1] J. S. Yeung, Y. Wong, and H. Xu, "Driver perspectives of open and tunnel expressways," *J. Environ. Psychol.*, vol. 36, pp. 248–256, Dec. 2013, doi: 10.1016/j.jenvp.2013.09.002.

[2] F. H. Amundsen and G. Ranes, "Studies on traffic accidents in Norwegian road tunnels," *Tunneling Underground Space Technol.*, vol. 15, no. 1, pp. 3–11, 2000, doi: 10.1016/S0886-7798(00)00024-9.

[3] R. Dang, J. Wang, S. E. Li, and K. Li, "Coordinated adaptive cruise control system with lane-change assistance," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 5, pp. 2373–2383, 2015, doi: 10.1109/TITS.2015.2389527.

[4] Y. Luo, Y. Xiang, K. Cao, and K. Li, "A dynamic automated lane change maneuver based on vehicle-to-vehicle communication," *Transp. Res. C, Emerg. Technol.*, vol. 62, pp. 87–102, Jan. 2016, doi: 10.1016/j.trc.2015.11.011.

[5] S. He, B. Liang, L. Tahkamo, M. Maksimainen, and L. Halonen, "The influences of tunnel lighting environment on driver's peripheral visual performance during transient adaptation," *Displays*, vol. 64, p. 101,964, Sep. 2020, doi: 10.1016/j.displa.2020.101964.

[6] L. Lin, W. Li, H. Bi, and L. Qin, "Vehicle trajectory prediction using LSTMs with spatial–temporal attention mechanisms," *IEEE Intell. Transp. Syst. Mag.*, vol. 14, no. 2, pp. 197–208, 2022, doi: 10.1109/MITS.2021.3049404.

[7] G. Guo and J. Liu, "A stochastic model-based fusion algorithm for enhanced localization of land vehicles," *IEEE Trans. Instrum. Meas.*, vol. 71, pp. 1–10, Mar. 2022, doi: 10.1109/TIM.2021.3137566.

[8] G. Guo and S. Zhao, "3D multi-object tracking with adaptive cubature Kalman filter for autonomous driving," *IEEE Trans. Intell. Veh.*, early access, 2022, doi: 10.1109/TIV.2022.3158419.

[9] T. Shim, G. Adireddy, and H. Yuan, "Autonomous vehicle collision avoidance system using path planning and model-predictive-control-based active front steering and wheel torque control," *Proc. Inst. Mech. Eng. D, J. Automobile Eng.*, vol. 226, no. 6, pp. 767–778, 2012, doi: 10.1177/0954407011430275.

[10] F. You, R. Zhang, G. Lie, H. Wang, H. Wen, and J. Xu, "Trajectory planning and tracking control for autonomous lane change maneuver based on the cooperative vehicle infrastructure system," *Expert Syst. Appl.*, vol. 42, no. 14, pp. 5932–5946, 2015, doi: 10.1016/j.eswa.2015.03.022.

[11] K. Chu, M. Lee, and M. Sunwoo, "Local path planning for off-road autonomous driving with avoidance of static obstacles," *IEEE Trans. Intell. Transp. Syst.*, vol. 13, no. 4, pp. 1599–1616, 2012, doi: 10.1109/TITS.2012.2198214.

[12] C. Zhang, Z. Deng, C. Wu, and X. Su, "Trajectory planning and tracking for autonomous vehicle based on state lattice and model predictive control," *IEEE Intell. Transp. Syst. Mag.*, vol. 11, no. 2, pp. 29–40, 2019, doi: 10.1109/MITS.2019.2903536.

[13] J. Zhou, H. Zheng, J. Wang, Y. Wang, B. Zhang, and Q. Shao, "Multiobjective optimization of lane-changing strategy for intelligent vehicles in complex driving environments," *IEEE Trans. Veh. Technol.*, vol. 69, no. 2, pp. 1291–1308, 2020, doi: 10.1109/TVT.2019.2956504.

[14] T. Pierre and B. Jacques, "Monotony of road environment and driver fatigue: A simulator study," *Accident Anal. Prevention*, vol. 35, no. 3, pp. 381–391, 2003, doi: 10.1016/S0001-4575(02)00014-3.

[15] D. F. Dinges, "An overview of sleepiness and accidents," *J. Sleep Res.*, vol. 4, no. 2, pp. 4–14, 1995, doi: 10.1111/j.1365-2869.1995.tb00220.x.

[16] Y. He, Z. Yang, and Y. Wang, "Experimental study on the interior aerodynamic noise characteristics of a car," *Autom. Eng.*, vol. 38, no. 1, pp. 72–77, 2016.

[17] W. Li et al., "Analysis of ear-side noise contribution of high-speed car drivers," *Noise Vib. Control*, vol. 39, no. 1, pp. 24–28, 2019.

[18] J. Hu and P. Wang, "Noise robustness analysis of performance for EEG-based driver fatigue detection using different entropy feature sets," *Entropy*, vol. 19, no. 8, p. 385, 2017, doi: 10.3390/e19080385.

[19] W. Zhao, "Analysis of human impact of noise in tunnel and research on active noise control system," Beijing Jiaotong University, Beijing, 2016. [Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD201602&filename=1016058792.nh

[20] J. Wang, A. Pervez, Z. Wang, C. Han, L. Hu, and H. Huang, "Crash analysis of Chinese freeway tunnel groups using a five-zone analytic approach," *Tunnelling Underground Space Technol.*, vol. 82, pp. 358–365, Dec. 2018, doi: 10.1016/j.tust.2018.08.037.

[21] K. Anton-Erxleben, K. Herrmann, and M. Carrasco, "Independent effects of adaptation and attention on perceived speed," *Psychol. Sci.*, vol. 24, no. 2, pp. 150–159, 2013, doi: 10.1177/0956797612449178.

[22] S. He, B. Liang, L. Tähkämö, M. Maksimainen, and L. Halonen, "The influences of tunnel lighting environment on drivers' peripheral visual performance during transient adaptation," *Displays*, vol. 64, p. 101,964, Sep. 2020, doi:10.1016/j.displa.2020.101964.

[23] S. He, B. Liang, G. Pan, F. Wang, and L. Cui, "Influence of dynamic highway tunnel lighting environment on driving safety based on eye movement parameters of the driver," *Tunnelling Underground Space Technol.*, vol. 67, pp. 52–60, Aug. 2017, doi: 10.1016/j.tust.2017.04.020.

[24] J. Nilsson, J. Silvlin, M. Brannstrom, E. Coelingh, and J. Fredriksson, "If, when, and how to perform lane change maneuvers on highways," *IEEE Intell. Transp. Syst. Mag.*, vol. 8, no. 4, pp. 68–78, 2016, doi: 10.1109/MITS.2016.2565718.

[25] J. Huang, Z. Ji, X. Peng, and L. Hu, "Driving style adaptive lane-changing trajectory planning and control," *China J. Highway Transp.*, vol. 32, no. 6, pp. 226–247, 2019, doi: 10.19721/j.cnki.1001-7372.2019.06.023.

[26] Q. Yuan, X. Xu, M. Zhao, and Y. Li, "The role of striking and struck vehicles in side crashes between vehicles: Bayesian bivariate probit analysis in China," *Accident Anal. Prevention*, vol. 134, p. 105,324, Jan. 2020, doi: 10.1016/j.aap.2019.105324.

[27] Q. Yuan and H. Chen, "Factor comparison of passenger-vehicle to vulnerable road user crashes in Beijing, China," *Int. J. Crashworthiness*, vol. 22, no. 3, pp. 260–270, 2016, doi: 10.1080/13588265.2016.1248226.

[28] H. Kui et al., "Fuel consumption model of automobile based on urban road conditions," *J. Jilin Univ. (Engineering Edition)*, vol. 39, no. 5, pp. 1146–1150, 2009.

[29] J. Huang, C. Yu, Z. Zhang, L. chen, and J. Yu, "Research on the actual measurement and noise reduction measures of urban tunnel noise," *Urban Roads Bridges Flood Control*, vol. 4, pp. 164–168, Apr. 2016.

[30] J. Ou, J. Yao, Y. Zhang, G. Deng, and E. Yang, "Experimental study on the effect of interior noise of vehicles on drivers' psychological character," *Noise Vib. Control*, vol. 29, no. 5, pp. 105–107, 2009.

[31] A. Spor, I. Kiyak, and G. Solak, "Artificial intelligence supported tunnel lighting system," in *Proc. 2019 Int. Conf. Appl. Autom. Ind. Diagnostics (ICAAID)*, pp.1–5, doi: 10.1109/ICAAID.2019.8934979.

[32] X. Hu, "Study on dynamic visual effect of high tunnel lighting on drivers," Chang'an Univ., Xi'an, China, 2018. [Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD201901&filename=1018791997.nh

[33] H. Zhao, D. Xia, S. Yang, and G. Peng, "The delayed-time effect of traffic flux on traffic stability for two-lane freeway," *Phys., A, Statal Mech. Appl.*, vol. 540, p. 123,066, Feb. 2019, doi: 10.1016/j.physa.2019.123066.

[34] S. Roger et al., "Low-latency layer-2-based multicast scheme for localized V2X communications," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 8, pp. 2962–2975, 2018, doi: 10.1109/TITS.2018.2870198.

[35] Q. Wang, Z. Li, and L. Li, "Investigation of discretionary lane-change characteristics using next-generation simulation data sets," *J. Intell. Transp. Syst.*, vol. 18, no. 3, pp. 246–253, 2014, doi: 10.1080/15472450.2013.810994.

[36] D. Yang, L. Zhu, B. Ran, Y. Pu, and P. Hui, "Modeling and analysis of the lane-changing execution in longitudinal direction," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 10, pp. 2984–2992, 2016, doi: 10.1109/TITS.2016.2542109.

[37] D. Yang, L. Zhu, F. Yang, and Y. Pu, "Modeling and analysis of lateral driver behavior in lane-changing execution," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2490, no. 1, pp. 127–137, 2018, doi: 10.3141/2490-14.

[38] D. Yang, S. Zheng, C. Wen, P. J. Jin, and B. Ran, "A dynamic lane-changing trajectory planning model for automated vehicles," *Transp. Res. C, Emerg. Technol.*, vol. 95, pp. 228–247, Oct. 2018, doi: 10.1016/j.trc.2018.06.007.

[39] Y. Yu, R. Jiang, and X. Qu, "A modified full velocity difference model with acceleration and deceleration confinement: Calibrations, validations, and scenario analyses," *IEEE Intell. Transp. Syst. Mag.*, vol. 13, no. 2, pp. 222–235, 2021, doi: 10.1109/MITS.2019.2898965.

[40] L. Ma, "Research on characteristics analysis of automated-manual vehicles traffic based on the cellular automata model," Southwest Jiaotong Univ., Chengdu, China, 2017. [Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD201702&filename=1017059161.nh

[41] M. Sivak, "The information that drivers use: Is it indeed 90% visual," *Perception*, vol. 25, no. 9, pp. 1081–1089, 1996, doi: 10.1068/p251081.

[42] C. Liu, "Research on vehicle trajectory and the characteristics of lane-changing behavior," Beijing Univ. Technol., Beijing, 2018. [Online]. Available: https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD201901&filename=1019700145.nh

[43] N. Liu et al., "Driving safety of extra-long tunnel based on reaction time characteristics of drivers," *Sci. Technol. Eng.*, vol. 20, no. 26, pp. 10,927–10,933, 2020.

[44] S. Yuan and Z. Guo, "A warning model for vehicle collision on account of the reaction time of the driver," *J. Saf. Environ.*, vol. 21, no. 1, pp. 270–276, 2021.

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