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Research Article

Expressway Lane Change in Fog Environment by Dynamic Strategic Game

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To study the behavior of expressway driver's lane change in a foggy environment, the driver's vision is adopted as the index for assessing the lane change behavior. The normalization theory is introduced to analyze the driver's intention of changing lanes. Using the statistical examination results of the driver's gaze zones, this paper has analyzed the gaze and glance features of the driver during the change of lanes. Based on the driving condition of changing lanes in foggy environment, the game theory is adopted in the study to elaborate on the strategy equilibrium of the driver's decision-making in the foggy environment. Moreover, a model is established to analyze the driver's lane changes under the foggy environment. Through the calibration of parameters and verification of the model, the reliability of the model has been proved. The research findings indicate that the features of the driver's gaze and glance under circumstances of the fine weather differ from those in the foggy environment, thus laying a theoretical foundation for the safety management of subsequent lane changes in the expressway in foggy environment.

1. Introduction

Visibility diminishes in the foggy environment, thus imposing an impact on the driver's vision and driving behavior. In general, the driver will decide to follow the front vehicle while driving on the expressway. However, when the speed and distance of the front vehicle could not meet the expectations of the driver of the rear vehicle, the driver will opt for the change of lanes. This is referred to as the passive change of lanes. In addition, there are circumstances when the driver proactively changes lanes, which is primarily linked with the driver's decision on driving behavior based on the analysis of the road conditions and the driving environment.

With respect to the studies on the lane change, Olsen et al. carried out a holistic study on the driver's lane changing behaviors based on the US natural driving data, including the frequency and duration of the lane change, acceptable spacing, and driver's gaze features [1]. Based on the data collected through the natural driving experiments in

Shanghai, Wang and Li have found that the driver's frequency of lane change is excessively high, and the driver tends to pay little attention to the blind spot prior to the lane change. In addition, the lane changing behaviors may vary on different roads [2]. However, due to the small size of sample on the pilots taking part in the experiments, their study rarely focuses on the behavior of varying types of drivers and is less convincing.

The earliest Gipps model on the lane change is based on a series of models on the fixed-condition decision tree. According to the model, whether the driver decides to change lanes or not depends primarily on the possibility and necessity of changing lanes as well as the driver's strong desire to do so [3, 4]. Based on the Gipps model, Hidas divided the lane changing behaviors into three categories, i.e., free lane change, cooperative lane change, and forced lane change, and set up the SITRAS model accordingly [5]. Kesting et al. put forward the MOBIL model based on the control of acceleration [6]. The value of vehicle acceleration is adopted to characterize the driving benefits made available

to the driver. By comparing the overall changes of the benefits of the locally affected vehicle on the current lane and the target lane before and after the lane change, the driver will decide whether or not to proceed with the change of lanes.

Hogema et al. put forward a utility-selective lane changing model, which assumes that the driver's motivation of changing lanes is derived from the comparison of varying values of lane utility. The probability of lane selection is illustrated through the function of the lane utility [7]. Toledo et al. carried out an in-depth study on the model and put forward a utility-selective lane changing model that takes into account both the free lane change and the forced lane change [8]. With closer attention paid to the psychological response features of drivers, the artificial intelligence model began to be applied to the study on lane changing behaviors, such as the model on the artificial neural network [9, 10].

The studies on the lane changing model at home and abroad have been carried out in a more in-depth manner [11–13], and some of the latest research on driving behavior and traffic forecasting [14, 15] but there are still some problems. First, the impact imposed by the driver features on their decision-making related to the lane change is over-simplified, and the relationship between the two is rarely analyzed in a quantitative manner. Second, the majority of the current studies fail to take into account the impact of surrounding vehicles and road conditions on the driver's decision-making on the lane change, there is little research on the influence of geometric features and environment of roads on the driver's lane changing behaviors, and fog is not even mentioned among the limits of current models. The driver's attempt to change lanes in vain is not taken into account while making corrections to the model. In the microscopic models, macro data are primarily adopted to verify the assessment, thus laying a theoretical foundation for the safety management of subsequent lane changes in the expressway in foggy environment.

2. Methods

2.1. Instruments. To determine the visual characteristics of the driver under lane maintenance conditions, a test was performed using a Smart Eye 5.7 noncontact eye tracker having an acquisition frequency of 60 Hz. The data include visual parameters such as the driver's fixation, sweeping, and blinking. And the test used the CJY-2B visibility meter to obtain the visibility.

2.2. Coordinate System. The changes in the driver's fixation angle reflect the distribution of the fixation areas and position of the fixation points. Different roads, visibility condition, and traffic conditions influence the change in the driver's viewing angle. The viewing angle of the eye movement apparatus defines the origin of the spatial coordinate system as the starting position of the viewing angle. It takes the angle, in radians, between this origin and the driver's line of sight as the driver's viewing angle [16].

2.3. Natural Driving Test. The research section is the G5013 Expressway from Bishan to Dazu and the G50S highway in the main city of Chongqing to the Shuanghekou section. The lane width is 3.75, m and the number of lanes is 3. We chose a large car (Hongyanjingang, vehicle height: 3.51 m, length: 8.73 m, width: 2.55m), a small car (Modern Rena, vehicle height: 1.46 m, length: 4.3 m, width:1.705m), and 15 drivers (normal drivers with no bad driving habits). In the actual vehicle test in the foggy environment, the driver is free to travel during the test. There is no human interference. A test of the driver's visual characteristics on a road section in a foggy zone of the expressway needs to use a real car to carry out the test under natural conditions. Studies have shown that the impact on the traffic environment is negligible when the visibility is greater than 500 m. So, to simplify the follow-up analysis of the test data, the selection of the test data is limited to visibility less than 500 m [17].

3. Collection of Experimental Data

The data on the driving behaviors under non-free flow conditions are mainly obtained through drones, traffic video surveillance, vehicle inspection device of transportation departments, and manual observation. While selecting data obtained through the vehicle inspection, the data with lane occupancy rate at or above one is selected. On the other hand, during the manual observation, the headway distance is mainly adopted for screening. When the headway distance is greater than 5 s, such driving behavior is regarded as free driving, and related data is removed from the selection of data.

Statistical analysis of the driver's traffic flow during the lane change is carried out based on the use of the obtained parameters including but not limited to visibility, speed of front vehicle, speed of rear vehicle, front lane, rear lane, headway distance, and line spacing of front lane as well as that of rear lane.

In addition, the Smart Eye Pro 5.7 eye tracker was applied in the collection, saving, and analysis of the dynamic visual parameters of the driver during driving.

4. Analysis of Features of the Driver's Lane Change Based on the Visual Gaze Zone

4.1. Analysis of the Driver's Intention to Change Lanes in Foggy Environment. During the study, the normalization theory is introduced into the correction of the driver's gaze zone during the change of lanes [18]. Based on the reference ratio, the gaze range of varying drivers is modified, and the data fusion is eventually carried out to set up the reference gaze zones of varying drivers [18].

The lane changing behaviors described in the eye-tracking test are from slow to fast vehicles. The specific normalization results are shown in Figure 1.

In addition, based on the law of distribution of the arrival of vehicles during foggy days, experimental vehicles are generally driven in the slow lane on the right side during the driving experiments in the fog environment. The factor contributing to the change of lanes is that the preceding
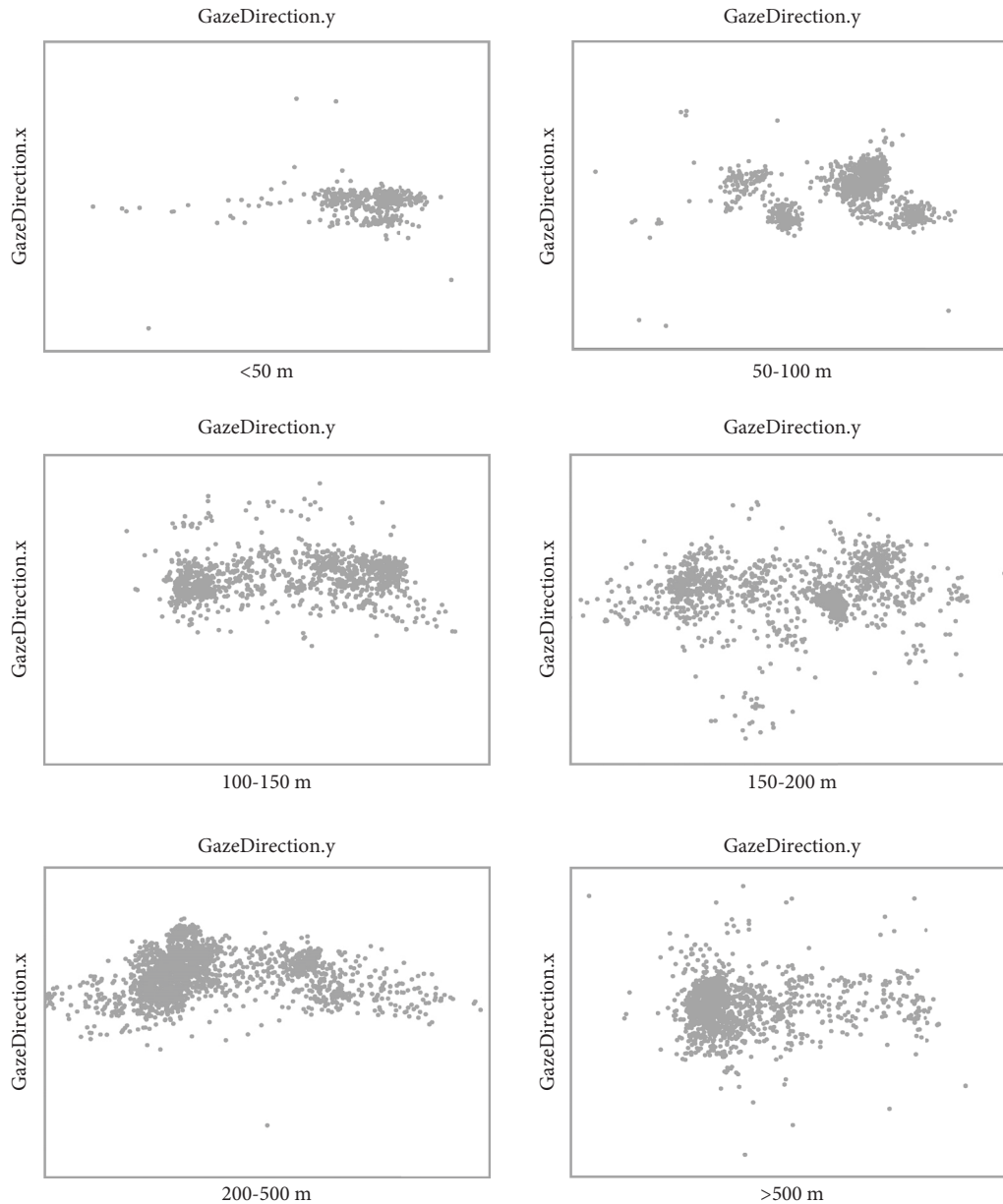
FIGURE 1: Normalization results of the center of gravity of the driver's lane changing gaze area under different visibility.

vehicle could not meet the speed requirement of the experimental vehicle. Consequently, the driver decides to change from the right lane into the left lane, namely, the leftward lane changes. The lane changes illustrated during the eye movement experiments all result from the driving behavior of changing from a slow lane into a fast one.

A descriptive experiment is conducted on the displacement of the point of gaze of the driver under low visibility. The experimental results are specified in Table 1.

Table 1 has specified the normalized results of the center of gravity of the driver's visual gaze zone during the change of lanes under low visibility, which indicate evident discrepancy in the driver's gaze zones. While driving under low visibility, the discrepancy in the gaze features exhibited by varying drivers is gradually weakened. Through the analysis of the difference of the gaze zones of 15 drivers, it is found that the driver's visual difference experiences gradual declines with the diminishing visibility. According to the observation of traffic behaviors, when the visibility is lower than 50 m, the driver's gaze zone is concentrated in the preceding vehicle. Moreover, based on the calculation, the measured probability of the driver's change of lanes under such circumstances reaches only 0.5%, and the probability crossing the line is increased to 44.6%.

The curve on the difference of the center of gravity of the driver's gaze is illustrated in Figure 2. Judging from Figure 2 and Table 1, the following conclusions can be reached on the driver's gaze zone under low visibility.

TABLE 1: Descriptive experimental results on the center of gravity of the driver's visual gaze zone during the change of lanes.

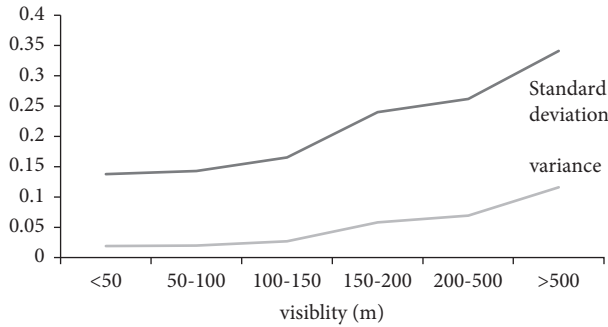|	N	Range	Minimum	Maximum	Mean	Std. deviation	Variance
<50	2000	1.27	−0.45	0.81	0.3143	0.00308	0.019
50–100	2000	1.29	−0.68	0.62	0.2152	0.00319	0.020
100–150	2000	1.54	−0.82	0.73	0.1371	0.00369	0.027
150–200	2000	1.37	−0.47	0.90	0.6547	0.00536	0.058
200–500	2000	1.00	0.00	1.00	0.6426	0.00586	0.069
>500	2000	0.96	0.00	0.96	0.5119	0.00763	0.116

FIGURE 2: Curve on the difference of the center of gravity of the driver's gaze under low visibility.

(1) When the visibility is lower than 50 m, based on the results of the video observation of the eye tracker, the driver's change of lanes is mainly based on the front vehicle as well as the road marking. Under such circumstances, the driver's lane changing behavior is mainly categorized as the forced change of lanes, and the front vehicle is either stationary or driven at an extremely low velocity, which affects the normal driving of the rear vehicle. Based on the statistical analysis, the attention paid by the driver to the front vehicle during the change of lanes amounts to 87%, whereas the attention paid to the road ahead and the road marking only amounts to 12%. Such visual behavior is likely to result in heightened risk of scratching and collision between the front vehicle and the rear vehicle. Based on the consequences of such visual behavior, it is recommended by the study that when the visibility is lower than 50 m, the driver should keep driving the vehicle and avoid changing lanes, except under extreme conditions such as when the preceding vehicle is stationary or driven at a velocity below 30 km/h.

(2) When the visibility ranges between 50 m and 100 m, the center of gravity of the point of gaze of the driver is also concentrated on the position of the front vehicle, but the driver's judgment on the road condition has been enhanced to a significant extent. Based on the observation of the velocity of the vehicle, the vehicle speed mainly ranges between 50 km/h and 70 km/h, with the speed being rarely lower than 50 km/h. Under such circumstances, the aggressive driver often opts for the change of lanes. The rate of lane changes is increased from 0.5% when the visibility is lower than 50 m to 5.2%, and certain vehicles can reach a speed of 70 km/h and even 80 km/h in extreme cases. Judging from the distribution of the center of gravity of the driver's gaze zones, it can also be found that the driver's gaze center is still near the front area, which has indirectly shown that the visibility could not meet the requirements of parking in terms of the line of sight. Therefore, it is recommended that the driver that intends to change the lanes under such circumstances should take careful steps and keep the distance between the front vehicle and the guardrail, so as to avoid scratches and rear-end collisions.

(3) Similar to the behavior of vehicle following, when the visibility falls within the range of [100 m, 150 m] and [150 m, 200 m], the difference of features of the driver's gaze is limited within the range. However, based on the discrete analysis of the center of gravity of the gaze zone, when the visibility is greater than 150 m, the standard deviation of the driver's gaze zone reaches 0.24, and there is a discrepancy with the center of gravity dispersion of 0.16 when the visibility is lower than 150 m. In addition, it can be clearly seen from the discrete curve that with the increases of visibility, the discrepancy among drivers is gradually manifested. At this moment, the driver's change of lanes is supported by visual conditions.

(4) When the visibility is greater than 200 m, the driver focuses on the target lane while changing lanes. The attention paid to the vehicle ahead mostly exists in the form of gaze, and the ratio of gaze is reduced to a significant extent. Moreover, the driver's habits and difference of gaze have unique features. Judging from the research findings on the normalized experiments of the center of gravity of the overall gaze zone, when the visibility is greater than 200 m, the standard deviation and variance of the center of gravity of the gaze zone are significantly different from those in the case of visibility lower than 200 m. As the visibility increases, its impact on the driver's gaze during the change of lanes is gradually weakened, and the driver has a lower level of relaxation. However, due to the impact imposed by the visibility on the surrounding environment, sign recognition, and road visibility, drivers are still recommended to drive carefully in foggy conditions.

4.2. Visual Features of the Driver's Change of Lanes in Foggy Environment. Similar to the vehicle-following procedure, the time window of driver's intention during the change of

lanes amounts to 5 s, and the data on the eye movement lasting for 5 s before and after the change of lanes are selected for analysis.

The driver's lane maintains the breadth of visual search under low visibility, as illustrated in Figure 3. The speed of driver's shift of point of gaze stands for the speed of driver's processing of visual information as well as the speed of search of information. The larger the speed, the greater the driver's searching demands for the gaze target. The driver's speed of visual search during the change of lanes is illustrated in Figure 3.

As shown in Figure 3, the driver's average breadth of search amounts to 21.0° during the change of lanes, and that of the lane keeping can only reach 9.8°. The experimental findings indicate that the driver is apparently going through the procedure of searching targets at this point, and the overall breadth of visual search is rather extensive. In addition, at this moment, the driver is recognizing and identifying the entire shapes and lines of roads. Subsequent to the completion of the change of lanes, the driver resumes the normal driving, thus resulting in lower breadth of visual search.

As shown in Figure 4, the speed of driver's saccade is lower during the normal lane keeping procedure. However, during the change of lanes, the speed of driver's saccade is subject to huge volatility with higher average speed of saccade. The results indicate that the driver has a large range of gaze during the change of lanes, and the dispersion is high, which is also conclusion on the breadth of the driver's visual search.

In addition, under circumstances of low visibility, the speed of the driver's shift of the point of gaze when changing lanes can reach 45.0, much lower than 52.0 in the fine weather. Such findings indirectly manifest that the breadth of the driver's visual search is reduced under lower visibility, and the driver is found to be in the stage of cautious driving, thus paying less attention to the information on both sides.

5. Modeling of the Lane Changing Behavior in the Foggy Environment Based on the Visual Game

5.1. The Driving Conditions in Foggy Days. Based on the driving experiments and monitoring data obtained in the foggy environment, it is found that the change of lanes takes place less frequently in the foggy environment. In general, when a slow-driving vehicle or other obstacles exist in the front, the driver is forced to change lanes. When the speed of the current vehicle could not match the demand of the rear vehicle, the driver will be obliged to change lanes in the foggy environment. Existing studies indicate that when the driver is obliged to change lanes, the acceptable safe distance for the driver is generally reduced by 20%.

There are three sorts of dangerous circumstances when the vehicle engages in the lane changing behavior [3]. First, the rear-end collision takes place between the lane changing vehicle and the preceding vehicle in the current lane due to untimely change of lanes. Second, subsequent to the change
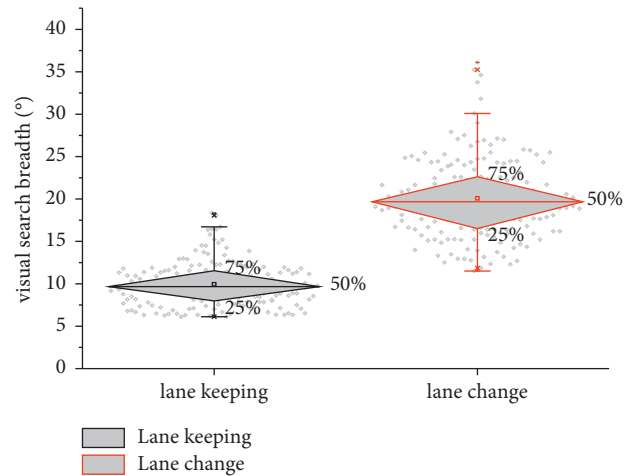

Figure 3: Statistical results on the breadth of the driver's visual search during the change of lanes.
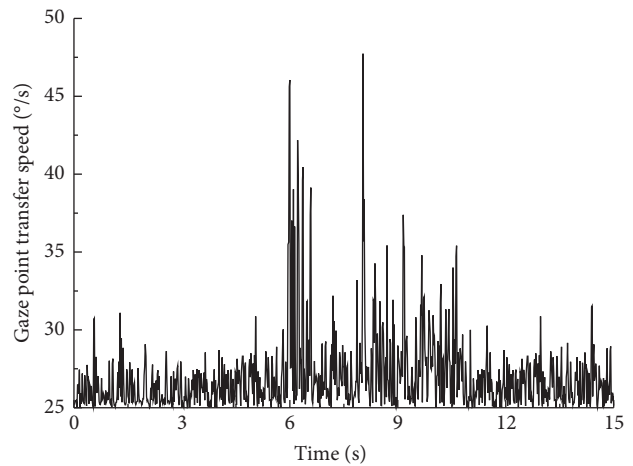

Figure 4: Speed of the shift of the point of gaze during the change of lanes.

of lanes, the current vehicle is hit from behind due to insufficient spacing in the expressway. Third, subsequent to the change of lanes, the distance between the current vehicle and the preceding vehicle in the target lane is too short for the driver to put on the brakes in time.

The time required for the vehicle to cross the lane with the length of 3.75 m during the change of lanes is obtained by the following formula:

$$\Delta t = \frac{L}{V_y} \qquad (1)$$

where V_y is the lateral velocity of the vehicle, m/s.

According to the current research findings, the lateral velocity ranges between 1.0 m/s and 1.5 m/s, and the value of Δt ranges between 2.5 s and 3.75 s. In case of consistence with (1), the lane changing vehicle can smoothly complete the change of lanes as long as the aforementioned three dangerous circumstances do not occur, and the scenario that the lane changing vehicle rushes out of the lane is not discussed in the paper.

(1) To avoid rear-end collision between the lane changing vehicle 1F and the preceding vehicle 2L in the current lane due to untimely change of lanes.

This process can be divided into the following procedures: The driver needs to accelerate the vehicle to surpass the rear vehicle 2F in the target lane before overtaking. On the other hand, the driver should also meet the demands for ensuring the safe distance L with the front vehicle, so as to avoid excessive acceleration and utterly limited distance of the vehicle that risks leading to rear-end collision with the rear vehicle 2L. Assuming that the acceleration of the vehicle amounts to a within $\Delta t/2$, the following formula shall be satisfied [3]:

$$V_{1F}\left(\frac{t + \Delta t}{2}\right) = V_{1F}(t) + \frac{a\Delta t}{2}. \quad (2)$$

At this point, the condition of avoiding the collision between the rear vehicle and the preceding vehicle is as follows:

$$X_{1F}(t) + V_{1F}(t) \cdot \frac{\Delta t}{2} + \frac{a\Delta t^2}{8}$$
$$\leq X_{1L}(t) + V_{1L}(t) \cdot \frac{\Delta t}{2} - L. \quad (3)$$

Judging from the aforementioned qualification condition, the speed of the front vehicle is constant, whereas the rear vehicle keeps driving in the original lane.

(2) To avoid rear-end collision between the lane changing vehicle 1F and the rear vehicle 2F subsequent to the change of lanes when the speed of 1F and its distance from 2F are too small to cause collision in the expressway.

This condition is primarily applied to prevent the lane changing vehicle from suffering from rear-end collision in the target lane after completion of the change of lanes. To meet the condition, the safe distance L needs to be kept between the lane changing vehicle 2F and the target lane vehicle 1F. Moreover, the speed of the target vehicle 1F is kept constant, whereas the lane changing vehicle 2F accelerates to depart, and the restraint conditions shall comply with the following formula:

$$X_{2F}(t) + V_{2F}(t)\Delta t$$
$$\leq X_{1F}(t) + V_{1F}(t) \cdot \Delta t + \frac{a\Delta t^2}{2} - L. \quad (4)$$

(3) To avoid rear-end collision between the lane changing vehicle 1F and the front vehicle 2L subsequent to the change of lanes due to the utterly short spacing and the untimely application of the brakes.

When the vehicle enters into the faster target lane from the current lane at a lower speed, it is generally going through an accelerated driving procedure. To avoid collision

with the rear vehicle in the target lane, the current vehicle may pick up speed, and yet the spacing between the two vehicles in the mode of lane keeping may not satisfy the need of the current vehicle to change lanes.

After the change of lanes by the vehicle 1F, to avoid collision with the rear vehicle in the target lane, the driver opts for the acceleration of the vehicle. However, in case the acceleration takes place too fast, the safe distance risks becoming insufficient, which is prone to cause collision with the front vehicle 2F in the target lane. Hence, it is necessary to ensure that the speed does not increase further in $\Delta t/2$ [7]:

$$X_{1F}(t) + V_{1F}(t) \cdot \Delta t + \frac{a\Delta t^2}{2} \leq X_{2L}(t) + V_{2L}(t) \cdot \Delta t - L. \quad (5)$$

Judging from the aforementioned formula, in the non-free flow state, the speed of the front vehicle and the spacing between the front and rear vehicles are the most vital factors that could impose an impact on the change of lanes. The primary issue faced by the driver is to identify ways of estimating the front vehicle speed and the distance while changing lanes. In the foggy environment, lower level of visibility could impose a dramatic impact on the driver's vision, thus undermining the driver's capacity of assessing the vehicle's spatial position and speed to varying extents. Hence, the driver is faced with heightened risk while changing lanes in the foggy environment, except when the following conditions are met:

$$X_{1F}(t) + V_{1F}(t) \cdot \Delta t + \frac{a\Delta t^2}{2} \leq X_{2L}(t) + V_{2L}(t) \cdot \Delta t - L. \quad (6)$$

In addition, it is necessary to comply with the perceived difference during the perception of the driver's field of view L_{fog}:

$$X_{1F}(t) + V_{1F}(t) \cdot \Delta t + \frac{a\Delta t^2}{2} \leq X_{2L}(t) + V_{2L}(t) \cdot \Delta t - L_{\text{fog}}. \quad (7)$$

In the foggy environment, the change of lanes shares similar features with the vehicle that engages in lane keeping, and it is necessary to assess the speed and distance of the vehicle. Moreover, the visibility can impose an evident impact on the driver's perception and processing of the visual information, thereby resulting in deviations in the assessment of the vehicle speed and the distance. Worse still, lower visibility could cause delay in the reaction time, and if the issue is not resolved in time, it risks leading to rear-end collisions or scratching accidents.

5.2. Analysis of Strategy Equilibrium and Model Development. In the foggy environment, the driver is generally involved in a dynamic game, and the game result of visual information is derived from the variations of visual behavior strategy. First, this study elaborates on the equilibrium features of the driver's visual behavior strategy in the foggy environment.

The behavioral strategies of the dynamic extensive game are selected first and foremost and are conducted several times in stages.

In addition, although the strategies of each participant engaged in the extensive game can be designed in advance, each participant is free to perform the selected action based on specific circumstances during the game as well as the progress of the game in each stage. Since the fundamental assumptions of the game theory are all targeted at maximizing the returns of the participants in the game, during the implementation of the game strategies, the participants are free to change their actions at any time during the game scheme as long as these actions are in the interests of the participants.

In the foggy environment, the driver is driving on the general road section during the experiments. When the front vehicle and the rear vehicle are in the state of operational balance, the driver of the rear vehicle decides on the game strategies of lane keeping, vehicle following, and change of lanes. Nevertheless, as long as the driver's driving expectation and satisfaction are ensured, the lane changing behavior will not take place, provided that the strategy of the Nash equilibrium is obtained during the game. A Nash equilibrium refers to a situation in a game where no player can improve their situation as long as the others do not change their strategies. Nash proved that a Nash equilibrium exists under the premise that each player has only a limited number of strategies to choose from and allows mixed strategies.

The driver's lane changing procedure in the foggy environment is a complex game of dynamic extension. It is necessary to simplify the structure of the game, so as to narrow the predictive range of the game solution. Therefore, the method of inverse induction is hereby introduced, and the unreliable factors in the game are identified through the examination of the computational properties.

The basic solution of the method of inverse induction lies in analyzing the selected behavior of the participants from the last stage of the game, and the reverse deduction is gradually carried out on the selected behavior of the corresponding participants in the previous stage, until the analyzed scenario is reversed to the initial stage of the game. We assume that the change of lanes is the final stage of the game and the strategy of lane keeping refers to the initial stage of the game q_1.

Moreover, the change of lanes is described as q_2. Lane keeping is the final stage of the driver's satisfaction, whereas the change of lanes only represents the completion of demands in stages. Ultimately, the driver is expected to the return to the original lane. During the whole course of the change of lanes, the driver is likely to return to the original lane at any time. Lane change q_2 is based on lane keeping q_1, and the driver decides on the vehicle speed, the lane change distance, and other traffic behaviors correspondingly. This procedure is a dynamic and perfect memory game due to the effects of selection before and after the game, and the lane keeping behavior serves as the foundation of the change of lanes.

Based on the establishment of the vehicle-following model and the analysis of the driver's visual features, the driver's change of lanes is divided into three procedures, namely, "demands for changing lanes, start of changing lanes, completion of changing lanes." When the demands arise for changing lanes, driver's visual parameters are obtained. Both the start and the termination of changing lanes are described through the use of the vehicle operating parameters. In this case, the indicator representing the driver's demands for changing lanes is the driver's saccade speed, and the change of lanes takes place and is completed with the description of the vehicle speed.

This analysis has integrated the visual behavior of the driver during the stage of intention of changing lanes, assuming that the visual intent of the lane keeping stage is referred to as q_1 and the lane changing intention is referred to as q_2. q_2 is based on q_1; namely, $q_2 = C_2(q_1)$. The visual strategy at equilibrium is represented as $[q_1, C_2(q_1)]$, and the benefit function is represented as $u_i[q_1, C_2(q_1)]$.

We assume that the inverse demand function is as follows:

$$\begin{aligned} P(Q) &= a - Q \\ &= a - q_1 - q_2. \end{aligned} \tag{8}$$

Then, the driver's satisfaction of driving is obtained as follows:

$$u_i[q_1, q_1] = q_i(P(Q)) = q_i(a - q_1 - q_2). \tag{9}$$

Subsequently, the objective function of lane keeping and lane change is as follows:

$$\begin{aligned} u_1 &= aq_1 - q_1q_2 - q_1^2, \\ u_2 &= aq_2 - q_1q_2 - q_2^2. \end{aligned} \tag{10}$$

According to the modeling on the procedure of changing lanes, the change of lanes is carried out based on lane keeping. In other words, q_2 that stands for lane change is the optimal choice for a given situation q_1. Therefore, the first-order derivation is calculated on the aforementioned formula, and the first-order derivation conditions are as follows:

$$\begin{aligned} \max_{q_2 \Delta 0} & \; q_2 a - q_1 q_2 - q_2^2, \\ \frac{dL}{dq_2} &= a - q_1 - 2q_2 \\ &= 0, \\ C_2(q_1) &= q_2 \\ &= \frac{1}{2}(a - q_1). \end{aligned} \tag{11}$$

$C_2(q_1)$ refers to the response function for lane keeping when the driver is changing lanes. Based on the approach of inverse induction, the driver has made forecast on the reaction function $C_2(q_1)$ while changing lanes during the lane keeping procedure. Hence, the visual demand q_1 is maximized during lane keeping:

$$\begin{aligned} \max_{q \Delta 0} & \; u_1(q_1, C_2(q_1)) \\ &= q_1(a - q_1 - C_2(q_1)) \\ &= q_1\left[(a - q_1) - \frac{1}{2}(a - q_1)\right] = \frac{1}{2}q_1(a - q_1). \end{aligned} \tag{12}$$

The primary task while processing the varying visual information of the driver is to select the reference value for the driver's visual parameters. In case a is defined as the reference value for the driver's visual parameters, $a - q_1$ refers to the difference between the reference value and the visual parameter of the driver's vehicle following. In other words, $a - q_1$ refers to the variation of the driver's visual parameters during lane keeping. Under such circumstances of the change of lanes, the driver's saccade speed index is subject to the largest volatility. Therefore, the saccade speed is selected as the index representing the driver's visual demands during the change of lanes, and the discrepancy is described as the baseline difference between lane keeping and lane changing. For easier calculation, the formula is specified as $a - q_1 = \Delta\eta$.

To eliminate the visual difference of varying drivers, the ratio is measured between the saccade speed v_f of the driver in foggy days and the standard saccade speed v_n of the driver in sunny days, which is defined as the fogging influence coefficient specified as follows:

$$q_1 = \frac{v_f}{v_n}. \tag{13}$$

The visual demands for changing lanes are as follows:

$$
\begin{aligned}
C_2(q_1) &= q_2 \\
&= \frac{1}{2}(a - q_1) \\
&= \frac{1}{2}\Delta\eta.
\end{aligned}
\tag{14}
$$

The formula for maximizing the visual demands during the lane keeping is calculated as follows:

$$\max_{q\Delta0} u_1(q_1, C_2(q_1)) == \frac{1}{2}\Delta\eta \cdot \frac{v_f}{v_n}. \tag{15}$$

In foggy days, the driver is subject to the impact imposed by the visibility, and deviations exist in the assessment of vehicle speed, distance, and reaction time. Based on the existing research, the safe distance model based on parking line of sight is as follows [6]:

$$s_0 = v_0 \cdot t_0 + \frac{v_0^2}{2a_{\max}}. \tag{16}$$

To ensure the safety of the vehicle, the safe distance in the foggy environment should be twice the difference between the safety critical distance in clear weather and the visible distance of the driver.

$$v_0 \cdot \Delta(t_0 + t_i) + \frac{v_0^2}{2a_{\max}} \leq (2s_0 - s_{\text{fog}}). \tag{17}$$

Accordingly, the conversion formula for the reaction time t_i in foggy days is described as follows:

$$t_i = \frac{2s_0 - s_{\text{fog}} - v_0^2/2a_{\max}}{v_0} - t_0. \tag{18}$$

TABLE 2: Results of the braking acceleration and reaction delay time under low visibility.

v_0	20	40	60	80	100	120
$a_{\max}$	5.12	4.47	3.82	3.17	2.51	1.86
t_i			1.18	3.26	5.73	9.46

In particular, t_i refers to the delay time of driver response (s). s_0 refers to the safety critical distance under normal weather conditions (m). s_{fog} refers to the foggy visibility (m). $a_{\max}$ refers to the braking acceleration (m/s^2). v_0 refers to the vehicle's traveling speed (m/s). t_0 refers to the reaction time of the driver under normal weather conditions (s).

The results of the braking acceleration and reaction delay time under low visibility are specified in Table 2 based on the calculation.

Based on the lane changing model in the safe distance and the correction model for the reaction time in the foggy environment, the driver's game of visual demands finally evolves into L_{fog}, i.e., the issue of meeting the demands for safe intervals during the change of lanes in foggy days. The correction coefficient of the safe distance is determined by the visual demands, whereas the general change of lanes is carried out under normal weather. The model of the safe distance and the correction model for the reaction time are adopted to finally determine the value of L_{fog}. The model of the change of lanes in the foggy environment is specified as follows:

$$X_{1F}(t) + V_{1F}(t) \cdot \Delta t + \frac{a\Delta t^2}{2} \leq X_{2L}(t) + V_{2L}(t) \cdot \Delta t - L_{\text{fog}}. \tag{19}$$

5.3. Calibration of Parameters and Verification of the Model.
The determination of the value of L_{fog} mainly depends on the psychological acceptability of drivers in the foggy environment. Based on the driving distance between the rear view and the driver's visual demands under low visibility, the visual demand index is selected as the index of searching speed so as to normalize the indicator.

In addition, the experimental data are introduced into the analysis, including visibility, speed of the front and the rear vehicles, distance of the front and the rear vehicles, reaction delay time, and braking acceleration as known statistics:

$$
\begin{aligned}
&X_{1F}(t) + V_{1F}(t) \cdot \Delta t + \frac{a\Delta t^2}{2} \\
&= X_{2L}(t) + V_{2L}(t) \cdot \Delta t - L_{\text{fog}}.
\end{aligned}
\tag{20}
$$

The objective function would contribute to solving L_{fog} and Δt. Subsequently, the model is calibrated using the approach of differential evolution.

The results of calibration are specified in Table 3.

The data that are not subject to the calibration are selected for the verification of the model. The specific verification index is the time required for the vehicle to change lanes Δt, and 50 sets of data related to the change of lanes

TABLE 3: Statistical results of parameters.

| Visibility		Δt	L_{fog}
<50	Mean value	4.25	5.68
	Median	3.89	5.52
	Standard deviation	0.25	0.32
	Coefficient of variation	0.08	0.21
50–100	Mean value	3.96	9.95
	Median	3.87	9.84
	Standard deviation	0.24	0.11
	Coefficient of variation	0.13	0.09
100–150	Mean value	3.74	15.68
	Median	3.71	16.23
	Standard deviation	0.34	0.96
	Coefficient of variation	0.21	0.53
150–200	Mean value	3.68	21.35
	Median	3.59	22.36
	Standard deviation	0.22	0.43
	Coefficient of variation	0.18	0.16
200–500	Mean value	3.24	32.57
	Median	3.31	33.68
	Standard deviation	0.17	0.66
	Coefficient of variation	0.09	0.34
>500	Mean value	3.05	42.18
	Median	3.01	43.58
	Standard deviation	0.59	0.22
	Coefficient of variation	0.32	0.09
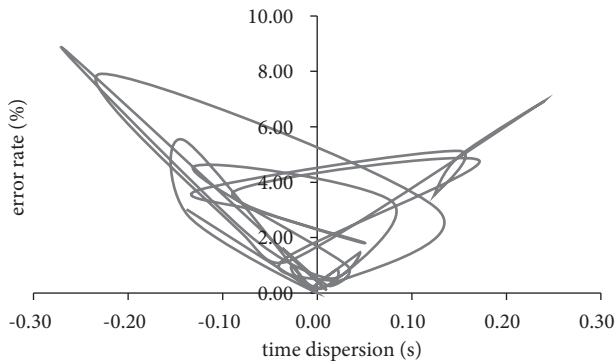
FIGURE 5: Diagram of the deviation and error ratio of the model parameter calibration experiments.

under low visibility are selected during the study. The deviation and error ratios of the transverse lane changing time of the vehicle are obtained through calculation. Certain data are illustrated in Figure 5.

Judging from the experimental results on the calibration of model parameters as well as the dispersion and error ratios, the maximum deviation of the transverse lane changing time of the vehicle estimated by the model amounts to 0.24 s, whereas the assessed maximum error ratio reaches 7.91%. Moreover, judging from the compactness of the diagram of deviation and error ratios, both the deviation and the error are biased toward the origin (0, 0). In other words, the error rate of the experimental results on the model tends to approach zero, and the sig value of the two-sided experimental result of the combined model is less

than or equal to 0.001. In addition, the model is verified within the confidence interval of 99%.

In a nutshell, the overall simulation of the lane changing model has shown better effects in the foggy environment based on the driver's visual game. This model is applicable to the assessment of the vehicle speed and the distance of the vehicle in the foggy environment, in addition to the marking line setting in the foggy environment. Moreover, in case the time required for changing lanes is longer and the speed is too slow, the driver should pay attention to the distance from the preceding vehicle and the consistence with the speed of the vehicle in the target lane during overtaking, so as to avoid collision and scratching accidents.

6. Conclusion

To study the behavior of expressway driver's lane change in the foggy environment, the driver's vision is adopted as the index for assessing the lane change behavior, and the normalization theory is introduced to analyze the driver's intention of changing lanes.

Using the statistical examination results of the driver's gaze zones, this paper has analyzed the gaze and glance features of the driver during the change of lanes. Based on the driving condition of changing lanes in foggy environment, the game theory is adopted in the study to elaborate on the strategy equilibrium of the driver's decision-making in the foggy environment. Moreover, a model is established to analyze the driver's lane changes under the foggy environment. Primary research findings are specified as follows:

(1) When the visibility is lower than 50 m, based on the results of video observation of the eye tracker, the driver's change of lanes is mainly based on the front vehicle and the road marking.

(2) Under lower visibility, the speed of the driver's shift of the point of gaze during the change of lanes can reach 45.0°/s, much lower than 52.0 s in the fine weather. Such findings indirectly manifest that the breadth of driver's visual search is reduced under lower visibility, and the driver is found to be in the stage of cautious driving, thus paying less attention to the information on both sides.

In addition, based on the driver's visual game, the lane changing model is established in the foggy environment. The results of calibration of the model parameters have verified the reliability of the model.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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