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Study on the Evolution Mechanism of Lane Change Decision in Urban Expressway Diversion Area

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Abstract: Urban expressway is the artery of modern urban traffic network, and the vehicle operation at off-ramp and diverging area affects the operation efficiency of the whole traffic system. The lane-changing game behavior between off ramp vehicles and going straight vehicles is very important in the whole driving behavior, and the lane-changing behavior between vehicles is easy to cause traffic accidents and stopping phenomena. To improve the driving efficiency in the diversion area and reduce the accident risk, by analyzing the process of the lane-changing behavior at off-ramp, this paper establishes a two-vehicle game model, solves the replicator dynamic equation according to the Dynamic Evolutionary Game Theory, uses MATLAB to calculate the evolution process and evolution speed based on different payoff factors, explores the influence of safety and speed on the stability of turn-out, and judges the evolutionary equilibrium point according to the determinant and trail of the Jacobi matrix. We build a realistic turn-out scenario and simulate it using the micro-traffic simulation software SUMO and it is found that: (1) The speed of different evolutionary equilibrium points based on speed payoff increased by 8.3% and 4.4% respectively compared with the speed of initial point. (2) The number of conflicts at the evolutionary equilibrium point based on the security payoff reduced to 22% of the initial point. (3) Compared with the initial point, the speed of the evolutionary stable point based on comprehensive payoff increased by 10.3%, and the number of conflicts reduced to 11% of the initial point. The simulation results show that the strategy of stable point of the evolutionary game model can effectively reduce the accident rate and improve the road operation efficiency.

Keywords: equilibrium point; evolutionary game; exit ramp; forced lane change; urban expressway

1 INTRODUCTION

By reason of the technical and ethical issues of autonomous vehicles, autonomous vehicles will gradually penetrate into the road traffic flow for a long time in the future, and human beings are still the main operators of vehicles. Although human driving vehicles cannot accurately calculate the payoff results and make completely rational decisions like machines, they can learn and find the most satisfactory decisions in the process of multiple lane changes. Human drivers with game behavior will thus gradually reach a stable strategy during lane changes.

The traffic behavior of urban expressway off-ramp includes lane-changing and straight driving, and the vehicle's off-ramp behavior is more complex than the straight driving operation, and the risk and accident rate are higher. The situation of vehicle operation on the off-ramp and diversion area of urban expressway directly affects the fast and stable operation of the expressway system [1]. When leaving the off-ramp, vehicles need to enter the ramp in the diversion area, and the lane change behavior in this process is mandatory. Forced lane change is different from free lane change. In order to avoid accidents, free lane change can be judged according to the density of the traffic flow. But in the forced lane change behavior on urban expressways, drivers often slow down, stop and wait, force queue-jumping and so on in order to drive out of the ramp when the distance between vehicles does not meet the demand of lane change, resulting in many potential safety hazards. In 2010, nearly 40% of the national expressway accidents occurred in the off-ramp area. According to relevant statistics, traffic accidents caused by wrong lane change decisions account for 27% of the total number of accidents. The traffic jam or accidents caused by the lane changing behavior itself and man-made strategic mistakes have brought great losses to the social economy.

Many scholars at home and abroad have studied the lane-changing behavior. Gipps [2] and his team established a model considering different lane-changing characteristics of drivers based on the gap acceptance threshold. Ahmed [3] established a model based on lane-changing rules, and considered that the lane-changing process includes three steps: lane-changing motivation, selecting possible lanes, and performing lane changing. Among them, a large number of scholars have modeled the lane-changing behavior based on the traditional game theory. Based on game theory, Kita [4] and his team established a lane-changing decision model, introduced the concept of "equilibrium choice probability", and jointly estimated the payoff and equilibrium choice probability in multiple equilibrium lane-changing games. Talebpour [5] and others established the optimal reflection function of lane change based on game theory, and solved the Nash Equilibrium as the basis for lane change decision. Based on complete information game, Yang Xiaofang [6] and others established a two-player game model to predict driving behavior, considering factors such as speed payoff and safety distance. It is found that the stable time of the game vehicle is longer in the smaller speed interval. Based on incomplete information game, Shang Ting [7] and others considered the safety payoff and speed payoff of both sides of the game based on different driving styles, established the forced lane change scenario at the exit of the tunnel, solved the perfect Bayesian Nash equilibrium as the lane change strategy, and found that the aggressive driver completed the forced lane change earlier than the cautious driver through Netlogo simulation. The model uses the value of patience to define the type of driver's aggressiveness and caution, and assigns the value of safety payoff and speed payoff, which has a certain degree of one-sidedness. For a long time in the future, with the development of intelligent network automobile and V2V technology, drivers or vehicles will get more and more information in the driving process, but due to technical constraints, the decision-making behavior of lane change is still incomplete information decision-making. Before the automatic driving of all vehicles is realized, the lane-changing decision of human-driven vehicles is still a bounded rational decision. Evolutionary game theory studies a dynamic learning process, which is different from the static equilibrium of traditional game theory. Evolutionary game shows that individuals achieve a stable equilibrium state through continuous trial and error and learning in decision-making.

Evolutionary game theory originated from the research of evolutionary biology in the 1980s, which reflects the idea of survival of the fittest and natural selection in biological populations. Maynard Simth [8] and others studied the phenomenon of biological population competition, discussed the mode of species evolution stability, and put forward ESS (Evolutionary Strategy Stable) to reflect the equilibrium solution of game stability, which originated from genetic and mutation theory and Darwin's theory of biological evolution, to simulate the law of survival of the fittest in the biological world. Many existing studies have applied evolutionary game to the game among the main bodies of urban transportation. Wei et al. [9] considered the willingness to cooperate, introduced evolutionary game theory to study traffic flow in urban networks, and simulation results show that stronger willingness to cooperate rather than simple more successful strategies can significantly promote the evolution of cooperation and relieve traffic pressure. Yoshiro et al. [10] used cellular automata to simulate the real traffic flow, and combined with the evolutionary game theory to realize the decision process of drivers, and found a social dilemma in the existence of self-centered lane change by drivers. Based on evolutionary game theory, Jiang Runsong [11] and others deduced the evolutionary stable point of different types of lane-changing strategies under different traffic density backgrounds, and found that the radical strategy was dominant under low traffic density, and the vehicle lane-changing decision tended to be rational under high traffic density. Based on the Jacobi matrix of the dynamic game, Du Xiaojing [12] and others established a game model of forced lane change when the intelligent network bus leaves the station, and found that by adjusting the safety and time payoff between the game vehicles through the overall optimal angle, the stable point of the evolutionary game can be adjusted, thus ensuring the safety and efficiency of more vehicles. Lu [13] and others proposed a Distributed Cooperative Routing algorithm (DCR) based on evolutionary game theory to coordinate vehicles. Compared with other five path planning algorithms, DCR can better balance traffic flow and reduce travel time due to evolutionary stability. In evolutionary games, when there is no strictly dominant strategy, mixed strategies should be considered, and the stability of mixed strategies in evolutionary games is often related to the initial distribution of the vehicles. Based on the modified S-NFS model, Tanimoto [14] and others considered the mixed flow of automatic driving and artificial vehicles, analyzed the stable state of lane-changing strategy under different traffic densities, and found that if all vehicles were artificial vehicles in the initial stage, automatic driving vehicles could not penetrate into society. Based on evolutionary game theory, Wei Liying [15] and others established a game model of whether to give way between pedestrians and vehicles, solved the replicator dynamic equation to obtain the equilibrium strategy, and explained the factors affecting the game theme payoff through sensitivity analysis, which provided a reference for the stable conditions of decision-making.

In the ramp diversion area of urban expressway, vehicles whose initial position is not in the rightmost lane need to change lanes to achieve the travel target, and when there are vehicles in the right front or in the right rear, they need to accelerate or decelerate to change lanes smoothly. At present, there are many accidents caused by drivers who drive on the diversion line or fail to pay attention to the vehicles coming from the rear after making a mistake in lane changing, and the lane changing behavior in this situation is not only easy to cause safety accidents, but also causes stopping, traffic jams and other phenomena when the vehicles coming from the right rear choose to accelerate and refuse, which not only increases the driving risk, but also increases the time cost. In this paper, a two-player game model is established to analyze the evolution mechanism of the forced lane-changing behavior of vehicles when they leave the exit ramp, and the stable strategy of the game between the vehicles leaving the exit ramp and the right rear vehicles is explored to establish a realistic road scene, and the stability of the evolutionary equilibrium point strategy is verified by using SUMO microscopic simulation software, which provides a feasible reference for road traffic safety and efficiency.

2 CONSTRUCTION OF GAME MODEL

2.1 Ramp Area Forced Lane Change Scenario

In the diversion area of urban expressway, in order to avoid pressing the diversion line, vehicles need to change lanes in the weaving area, at this time, the off-turn vehicles often need to play games with the rear vehicles. As shown in the Fig. 1, vehicle 1 and vehicle 2 are off-ramp vehicles, and vehicle 3 and vehicle 4 are straight-line vehicles. Vehicle 1 needs to change lane to enter the off-ramp. When there are vehicles in the right front and right rear of the lane-change vehicle, it first needs to consider the safe distance from the vehicle in the right front. If it is less than the safe distance from the vehicle in front, vehicle 1 will accelerate to overtake the vehicle in front to change lanes or decelerate to maintain the safe distance between the front and rear, and then play a game of changing lanes with the vehicle behind. In the Fig. 1, when the vehicle 1 turns on the turn signal, the vehicle body has partially pressed the line, that is, the forced lane change strategy is selected. The straight vehicle 3 does not choose to slow down and give way, but chooses to change lanes to the left to assist the vehicle 1 to change lanes successfully.

Figure 1 Off-ramp lane changing scenario

In the actual road conditions, the lane-changing behavior between vehicles is very complex. When the vehicle changes lanes, the main body first observes the situation behind the vehicle, sends a lane change signal after meeting the lane change conditions, and then selects the lane change strategy according to the information feedback of the rear vehicle. Due to the bounded rationality of human drivers, when they change lanes in actual driving, they are prone to perceptual bias in the process of "observing, sending signals, receiving signals and making decisions", especially when the lane-changing vehicles need to slow down to obtain safe lane-changing space, the following vehicles will speed up to refuse the demand of lane-changing vehicles in pursuit of the desired speed, which is prone to traffic accidents.

From the previous example, it can be seen that the strategy types of vehicle 1 include accelerating and changing lanes, queue-jumping and changing lanes, decelerating and waiting to change lanes, etc.; The strategy types of the right rear vehicle 3 include accelerating to refuse the front vehicle to change lanes, changing lanes to assist the front vehicle to change lanes, decelerating to give way, etc. Because the distance and speed of vehicles in the driving state are not fixed, human drivers can only judge whether they meet the lane-changing conditions by intuition and experience, and the choice of strategies is affected by the driving state of vehicles and the psychological factors of drivers.

In this paper, the strategy set is simplified, and there are two strategies for lane-changing vehicles, namely, change lane compulsorily and wait for changing lane. There are two strategies for straight vehicles, namely, accept to give way and refuse to give way. In actual driving, the order of lane-changing game behavior is as follows: lane-changing vehicle sends lane-changing signal → right-rear vehicle selection strategy → lane-changing vehicle selection strategy → right-rear vehicle selection strategy… Lane changing succeed/fail. Theoretically speaking, the lane-changing game is a repeated game, but due to the limitation of the length of the weaving section, the number of lane-changing games can be simplified to one, that is, after sending the lane-changing signal, when the rear vehicle chooses the strategy, the lane changing vehicle chooses the corresponding strategy to complete the game.

In this situation, the strategy combination of both sides of the game is (change lane compulsorily, accept to give way) (change lane compulsorily, refuse to give way) (wait for changing lanes, accept to give way) (wait for changing lanes, refuse to give way), and each strategy combination achieves different speed and safety gains.

S1: (change lane compulsorily, accept to give way): the rear vehicle chooses to yield, and the lane change vehicle chooses to change lanes. At this time, the lane-changing vehicle can successfully change lanes, although the lane-changing vehicle may transmit the information of forced lane change by accelerating at the beginning of the game, it needs to slow down due to the limitation of the length of the road section when merging, and the rear vehicle needs to slow down at the same time, so that the two vehicles gain safety payoff and lose speed in the process of lane changing.

S2: (change lane compulsorily, refuse to give way): the rear vehicle refuses to give way, and the lane change vehicle changes lanes compulsorily. If this strategy was executed, the vehicle would not be able to change lanes successfully and it would be easy to cause accidents. While losing time and security payoff.

S3: (wait for changing lane, accept to give way): The rear vehicle accepts to give way, and the lane-changing vehicle waits for lane change. Both of them obtain safety payoff, but the loss of time payoff is huge. The deceleration range is large and even the stopping phenomenon occurs.

S4: (wait for changing lane, refuse to give way): The rear vehicle refuses to give way, and the lane-changing vehicle waits for lane change. At this time, lane-changing vehicles choose to slow down or stop, losing time payoff. While the rear vehicle passes safely, it will also gain time payoff.

2.2 Evolutionary Game Model

In the actual driving process, what kind of driving behavior the driver takes is determined by the driver's traffic needs and motivation. Traffic demand mainly includes safety, economy, speed, continuity, independence, comfort and sociality. In this paper [16] , it is considered that the driver mainly considers the needs of safety and speed in the shorter path of the off-ramp interweaving section. Safety indicators include sudden braking, rear-end collision and side collision in the process of lane change. Rapidity indicators include the successful departure and running speed of lane-changing vehicles. If the lane change is not successful, the driver needs to take a detour and delay the travel time. Lane-changing vehicles stop or slow down in order to wait for the opportunity to change lanes, and when the threshold of successful lane-changing distance is reached, lane-changing vehicles will take forced lane-changing or queue-jumping. Vehicles coming from the right rear decelerate or change lanes in order to help them change lanes successfully, while accelerating or maintaining speed is to refuse to change lanes for their own speed payoff.

The influencing factors of the state include the own vehicle speed v, the own vehicle acceleration a, the front vehicle safety distance l_1 of the target lane, the rear vehicle safety distance l_2 of the target lane, and the distance L from the ramp entrance. The respective impacts are as follows:

Table 1 Influencing factors of vehicle strategy selection

v	It affects the safe spacing and the success rate of lane change, and needs to increase and decelerate if necessary.
a	Affect the safety of the vehicle. Sudden braking or acceleration can easily cause injuries to people in the vehicle or rear-end collision.
l_1, l_2	Affect the safety of the vehicle. If the requirements are not met, it is easy to cause rear-end collision or side collision.
L	Affect the success rate of lane change. The smaller the L is, the smaller the driver's patience is. And the driver is easy to force congestion or sudden braking to slow down and change lanes, and then cause safety accidents.

According to the lane-changing scenario analysis in the previous section, when both sides of the game choose the S_1 strategy combination, $U_{cv} = S_{11} - T_{11}$, which means that the lane-changing vehicle gains a little safety payoff and loses a little speed payoff. Under the S_3 strategy, $U_{cv} = S_{13} - T_{13}$, lane-changing vehicles gain more safety payoff, but lose more speed payoff due to waiting for lane-changing. That is, $T_{11} < T_{13}$, $S_{11} < S_{13}$. Under the S_1 and S_2 strategies, the rear vehicles all obtain greater safety payoff, but in the S_1 strategy, the speed loss is less due to the fact that the game can be ended after lane change, and the low-speed or stopping time is shorter. While in the S_3 strategy, both sides of the game will have game behavior again, and the speed loss is greater, that is, $T_{21} < T_{23}$, $S_{21} \le S_{23}$. Under the S_2 strategy combination, the lane-changing vehicle conflicts with the vehicle coming from behind, resulting in stopping or slowing down, and both sides lose large speed payoff and safety payoff at the same time, $S_{12} = S_{22} >$ MAX $\{S_{ij}, j \neq 2\}$, $T_{12} = T_{22} >$ MAX $\{T_{ij}, j \neq 2\}$. Under the S_4 strategy, the lane-changing vehicle obtains a larger safety payoff, and can change lanes after the rear vehicle goes straight, so it loses some speed payoff, while the rear vehicle obtains some safety payoff and a lot speed payoff, that is, $S_{14} > S_{24}$, $T_{14} < T_{24}$.

When the vehicle is in the game, the speed and safety payoff of both sides of the game are shown in the following Tab. 2.

Table 2 Payoff matrix of lane-changing game

Lane-changing vehicles \ Rear vehicles		q	$1-q$
		Accept to give way	Refuse to give way
p	Change lane compulsorily	$(S_{11}-T_{11}, S_{21}-T_{21})$	$(-S_{12}-T_{12}, -S_{22}-T_{22})$
$1-p$	Wait for the lane change	$(S_{13}-T_{13}, S_{23}-T_{23})$	$(S_{14}-T_{14}, S_{24}+T_{24})$

According to the state of vehicles when changing lanes, this paper makes the following assumptions about safety and speed payoff:

(1) In this paper, it is assumed that the safety payoff S is determined by *DRAC* (deceleration to avoid a crash), which represents the merging conflict and the conflict between the front and rear vehicles when the vehicle changes lanes in the process of leaving the off-ramp. *DRAC* effectively improves the reliability of the conflict because it takes into account the braking performance of the vehicle. $S = f(\text{count}(DRAC \ge 2), l_i)$.

$$DRAC = \frac{\Delta v}{\Delta t} = \frac{V_{\text{cv}} - V_{\text{rv}}}{\Delta t}$$

$\Delta t = f(l_i, V, a)$ is the time difference between the two sides of the game entering the conflict area.

When the lane-changing vehicle plays a game with the rear coming vehicle, if the lane-changing vehicle changes lanes compulsorily, a potential conflict area with the rear coming vehicle will be generated, and if the rear vehicle decelerates at a certain acceleration (*DRAC*) at this time to ensure that it enters the conflict area when lane-change vehicle leaves the conflict area, there will be no conflict. When the required acceleration is larger than *DRAC* and the vehicle's own braking performance is not satisfied, the conflict will occur.

(2) In this paper, it is assumed that the speed payoff T is determined by the average speed of vehicles in the diversion area.

$$T = \frac{\sum_{i=1}^{n} V_{\text{timestep}i}}{n}$$

(3) The smaller the distance L from the off-ramp entrance is, the higher the driver's impatience value is, and the higher the probability of forced lane change is.

In order to clearly reflect the payoff of each subject in the process of vehicle lane change in the off-ramp area, this paper simplifies the time and speed payoff as U_i, and considers the evolution process under different payoff elements in the following chapter.

$$U, V = \alpha S + \beta T$$

U represents the payoff obtained when the lane changing vehicle makes a decision, and V represents the payoff obtained when the rear vehicle makes a decision, and T_{ij} represents the speed payoff in vehicle game and S_{ij} represents the safety payoff in vehicle game.

Table 3 Comprehensive payoff of vehicle lane-changing game

Lane-changing vehicles \ Rear vehicles		q	$1-q$
		Accept to give way	Refuse to give way
p	Change lane compulsorily	(U_1, V_1)	(U_2, V_2)
$1-p$	Wait for the lane change	(U_3, V_3)	(U_4, V_4)

3 EQUILIBRIUM POINT ANALYSIS OF THE EVOLUTIONARY GAME

3.1 Replicator Dynamics Equation

(1) Replicator dynamic equation of lane changing vehicle

The expected payoff of lane changing vehicle (CV) choosing to change lane compulsorily is:

$$\begin{aligned} U_{\text{fc}} &= q(\alpha S_{11} - \beta T_{11}) + (1-q)(-\alpha S_{12} - \beta T_{12}) = \\ &= q(\alpha S_{11} - \beta T_{11} + \alpha S_{12} + \beta T_{12}) - (\alpha S_{12} + \beta T_{12}) = \\ &= qU_1 + (1-q)U_2 \end{aligned} \tag{1}$$

The expected payoff of lane changing vehicle (CV) choosing to wait for the lane change is:

$$\begin{aligned} U_{\text{wc}} &= q(\alpha S_{13} - \beta T_{13}) + (1-q)\ (\alpha S_{14} - \beta T_{14}) = \\ &= q(\alpha S_{13} - \beta T_{13} - \alpha S_{14} + \beta T_{14}) + (\alpha S_{14} - \beta T_{14}) = \\ &= qU3 + (1-q)U_4 \end{aligned} \tag{2}$$

When lane changing vehicles change lane compulsorily with p probability and wait for lane changing with $(1-p)$ probability, the average expected return is:

$$\begin{aligned} U_{\text{CV}} &= p\left(qU_1 + (1-q)U_2\right) + (1-p)\left(qU_3 + (1-q)U_4\right) = \\ &= pq(U_1 - U_2 - U_3 + U_4) + p(U_2 - U_4) + q(U_3 - U_4) + U_4 \end{aligned} \tag{3}$$

Replicator dynamic equation of the lane vehicle according to the above formula:

$$\begin{aligned} F_{\text{CV}}(p,q) &= \frac{\partial p}{\partial t} = \\ &= p(U_{\text{fc}} - U_{\text{cv}}) = p(1-p)(U_{\text{fc}} - U_{\text{wc}}) = \\ &= p(1-p)\left(q(U_1 - U_2 - U_3 + U_4) + U_2 - U_4\right) \end{aligned} \tag{4}$$

(2) Replicator dynamic equation of rear vehicle

The expected payoff of the rear incoming vehicle (RV) choosing to accept to give way is:

$$\begin{aligned} U_a &= p(\alpha S_{21} - \beta T_{21}) + (1-p)(\alpha S_{23} - \beta T_{23}) = \\ &= p(\alpha S_{21} - \beta T_{21} - \alpha S_{23} + \beta T_{23}) + \alpha S_{23} - \beta T_{23} = \\ &= pV_1 + (1-p)V_3 \end{aligned} \tag{5}$$

The expected payoff of the rear incoming vehicle (RV) choosing to refuse to give way is:

$$\begin{aligned} U_r &= p(-\alpha S_{22} - \beta T_{22}) + (1-p)(\alpha S_{24} + \beta T_{24}) = \\ &= p(-\alpha S_{22} - \beta T_{22} - \alpha S_{24} - \beta T_{24}) + \alpha S_{24} + \beta T_{24} = \\ &= pV_2 + (1-p)V_4 \end{aligned} \tag{6}$$

When the rear vehicle accepts to give way with probability q and refuses to give way with probability (1 − q), its average expected return is:

$$\begin{aligned} U_{RV} &= q\left(pV_1 + (1-p)V_3\right) + (1-q)\left(pV_2 + (1-p)V_4\right) = \\ &= pq\left(V_1 - V_3 - V_2 + V_4\right) + p\left(V_2 - V_4\right) + q\left(V_3 - V_4\right) + V_4 \end{aligned} \tag{7}$$

According to the above formula, the replication dynamic equation of the rear car can be obtained:

$$\begin{aligned} F_{RV}(p,q) &= \frac{\partial q}{\partial t} = q\left(U_a - U_{RV}\right) = \\ &= q(1-q)\left(U_a - U_{RV}\right) = \\ &= q(1-q)\left(pV_1 + (1-p)V_3 - pV_2 - (1-p)V_4\right) = \\ &= q(1-q)\left(p\left(V_1 - V_3 - V_2 + V_4\right) + V_3 - V_4\right) \end{aligned} \tag{8}$$

3.2 Solution of Equilibrium Point

In order to solve the evolutionary equilibrium point in the lane changing game, we need to solve the determinant |Jacobi| and tr(Jacobi) of its Jacobi matrix according to the replicator dynamic equation.

From the above formula, when p, q satisfy the following formula, we can get all the evolutionary game equilibrium points.

$$\begin{cases} \dfrac{\partial p}{\partial t} = 0 \\ & p, q \in [0,1] \\ \dfrac{\partial q}{\partial t} = 0 \end{cases} \tag{9}$$

$$\begin{aligned} F_{cv}(p,q) &= \frac{\partial p}{\partial t} = \\ &= p(1-p)\left(q\left(U_1 - U_2 - U_3 + U_4\right) + U_2 - U_4\right) \end{aligned} \tag{10}$$

$$\begin{aligned} F_{rv}(p,q) &= \frac{\partial q}{\partial t} = \\ &= q(1-q)\left(p\left(V_1 - V_3 - V_2 + V_4\right) + V_3 - V_4\right) \end{aligned} \tag{11}$$

Regardless of the values of U_1, U_2, U_3, U_4, V_1, V_2, V_3, and V_4 in the model, (0, 0), (0, 1), (1, 0), (1, 1), ($p^* = (V_4 - V_3)/(V_1 - V_3 - V_2 + V_4)$; $q^* = (U_4 - U_2)/(U_1 - U_2 - U_3 + U_4)$) are the equation solutions.

When $V_1 = V_2$ and $p = 1$, q takes an arbitrary value; When $U_1 = U_3$ and $q = 1$, p takes an arbitrary value. If $U_1 = U_3$, $U_2 = U_4$, $V_3 = V_4$, $V_1 = V_2$, p and q can be any values.

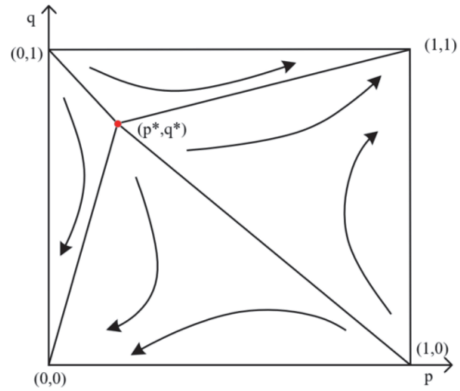


Figure 2 Phase diagram of equilibrium points

Table 4 Determinants and traces of the Jacobi matrix

Equilibrium point	|Jacobi|	tr(Jacobi)
(0, 0)	$(U_2 - U_4)(V_3 - V_4)$	$U_2 - U_4 + V_3 - V_4$
(0, 1)	$(U_1 - U_3)(V_4 - V_3)$	$U_1 - U_3 + V_4 - V_3$
(1, 0)	$(U_4 - U_2)(V_1 - V_2)$	$U_4 - U_2 + V_1 - V_2$
(1, 1)	$(U_3 - U_1)(V_2 - V_1)$	$U_3 - U_1 + V_2 - V_1$
$((V_4 - V_3)/(V_1 - V_3 - V_2 + V_4), (U_4 - U_2)/(U_1 - U_2 - U_3 + U_4))$	$[(V_1 - V_2)(V_4 - V_3)(U_1 - U_3)(U_4 - U_2)]/[(V_1 - V_3 - V_2 + V_4)(U_1 - U_2 - U_3 + U_4)]$	0

$$\text{Jacobi} = \begin{pmatrix} \dfrac{\partial F_{cv}(p,q)}{\partial p} & \dfrac{\partial F_{cv}(p,q)}{\partial q} \\ \dfrac{\partial F_{rv}(p,q)}{\partial p} & \dfrac{\partial F_{rv}(p,q)}{\partial q} \end{pmatrix} = \begin{pmatrix} (1-2p)\left(q\left(U_1 - U_2 - U_3 + U_4\right) + U_2 - U_4\right) & p(1-p)\left(U_1 - U_2 - U_3 + U_4\right) \\ q(1-q)\left(V_1 - V_3 - V_2 + V_4\right) & (1-2q)\left(p\left(V_1 - V_3 - V_2 + V_4\right) + V_3 - V_4\right) \end{pmatrix}$$

According to the positive and negative of the trace, we can judge the stability point of the evolutionary game. When |Jacobi| > 0 and tr(Jacobi) < 0, that point for the stable point.

4 ANALYSIS OF DYNAMIC EVOLUTIONARY GAME BASED ON DIFFERENT KINDS OF REVENUE

The evolutionary stable strategies of group games are not only different due to the different initial probability distributions, but also their payoff affects the evolutionary stable trend. In the traditional game lane-changing model, some scholars [17, 18] consider speed as the only payoff parameter, and some scholars [19] combine speed and spatial distance as payoff. Due to the single setting of payoff parameters, there is a certain deviation from the actual driving environment. During the off-ramp and lane change process, the driver will increase the time payoff under the premise of satisfying the safety payoff, and the corresponding game vehicle will guarantee the speed under the premise of meeting the safety payoff. Different groups have different feelings about the weight and utility of different payoff elements, so this paper uses The two dimensions of time (speed) and space (security) as the main dimensions, and the stable trend of game evolution under different payoff elements and different weights are discussed respectively.

Table 5 Payoffs of group strategy in game

Rear vehicle \ Lanechanging vehicle	Accept to give way	Refuse to give way
Change lane compulsorily	$S_1(U_1, V_1)$	$S_2(U_2, V_2)$
Wait for the lane change	$S_3(U_3, V_3)$	$S_4(U_4, V_4)$

4.1 Evolutionary Stability Analysis Based on Security Payoff

The safety payoff in normal driving state is 0. When the player chooses the strategy combination S_1, the lane-changing vehicle obtains a small payoff due to its riskiness, and the rear vehicle obtains a large payoff. When S_2 is selected, both parties are most likely to have a collision accident, and both sides will lose a lot of safety payoffs. When S_3 is selected , both parties will slow down or stop at the same time, and at the same time obtain greater safety payoffs. When S_4 is selected , the lane-changing vehicle obtains greater safety payoff due to its conservatism, and the rear vehicle obtains less safety payoff due to its adventurousness.

This paper assumes that the security payoff $U_1 = 50$, $U_2 = -150$, $U_3 = 100$, $U_4 = 100$, $V_1 = 100$, $V_2 = -150$, $V_3 = 100$, $V_4 = 50$. (U and V below represent security payoff)

(1) Analysis of evolution process

According to Fig. 3, when $(p, q) = (1, 0), (0, 1), (0, 0), (1, 1)$, both sides of the game are at the equilibrium point.

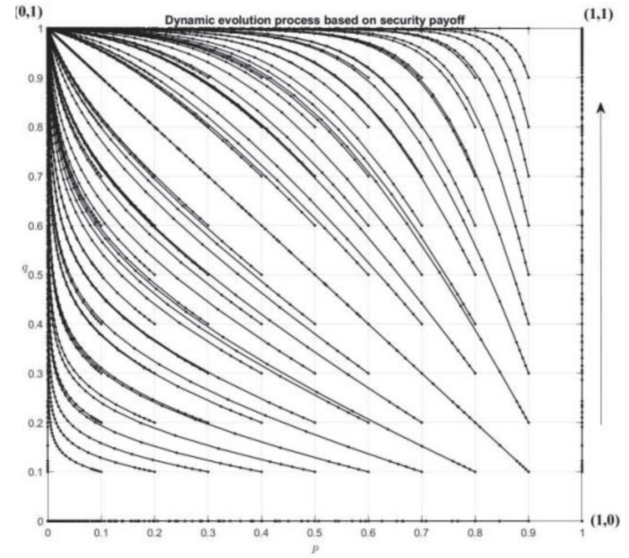


Figure 3 Dynamic evolution process based on security payoff

Table 6 Evolutionary stable points based on security payoff

Equilibrium point	|Jacobi| symbol	tr(Jacobi) symbol	Equilibrium type
(0, 0)	−	−	Uncertain point
(0, 1)	+	−	Stable point (ESS)
(1, 0)	+	+	Unstable point
(1, 1)	−	−	Uncertain point
(p^*, q^*)	+	0	Center point

The point (1, 0) means that the lane-changing vehicles must choose to change lanes compulsorily, and the vehicles coming from behind must choose to refuse to give way. When there is a "mutation" of the car coming from behind, that is, when $q > 0$, the strategic stability points of the two players in the game change to point (1, 1) . Strategy. When the lane-changing vehicle "mutates", that is, when $p < 1$, the strategy selection of the lane-changing vehicle gradually evolves to $p = 0$, that is, it chooses to wait for the lane-changing when the vehicle behind refuses.

The point (0, 0) means that the lane-changing vehicle must choose to wait for the lane change, and the vehicle coming from behind must choose to refuse to give way. When the lane-changing vehicle "mutates", that is, $p > 0$, the lane-changing vehicle chooses to force the lane-changing with a certain probability, that is, the strategy combination S_2. At this time, the payoff of the lane-changing vehicle after the "mutation" decreases, and the strategy selection of the mutation will disappear in the evolution, that is, returns to the (0, 0) stable point. When the car coming from behind "mutates", that is, $q > 0$, the security payoff obtained by the strategy of the car coming from behind is greater than the payoff obtained when $q = 0$, and then q gradually tends to 1, and the evolutionary stable point is (0, 1) .

The point (1, 1) means that the lane-changing vehicles must choose to change lanes compulsorily, and the vehicles behind must choose to give way. When the lane-changing vehicle "mutates", that is, when $p < 1$, the lane-changing vehicle chooses to wait for the lane-changing with a certain probability, and the safety payoff obtained is greater than the payoff before the mutation. At this time (1, 0) is the evolutionary stable point. When there is a "mutation" in the car coming from behind, choose to refuse to give way. At this time, the payoff decreases, the mutation strategy disappears, and it still returns to the (1, 1) stable point.

Under other probability combinations, the co-evolutionary trends are $p \to 0$ and $q \to 1$. The final evolutionary stable point is (0, 1), that is, the strategy combination is (wait for lane change, accept to giveway).

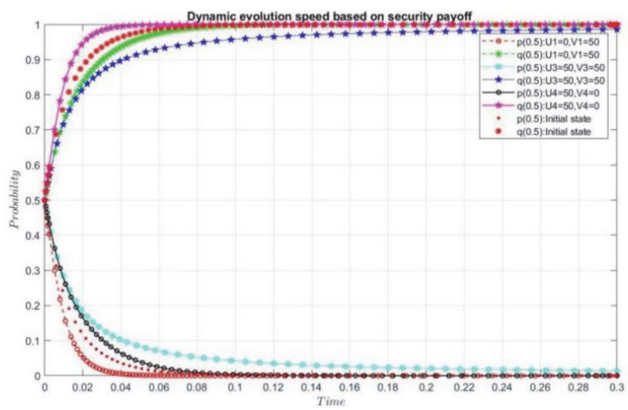


Figure 4 Dynamic evolution speed based on security payoff

(2) Analysis of the speed of the evolution

In this paper, $(p, q) = (0.5, 0.5)$ is selected as the initial probability, and the evolution convergence speed under different security payoff is analyzed. It can be seen from Fig. 3 that all unstable points eventually converge to (0, 1), that is, the strategy combination S_3, and this stable point is related to U_1, U_3, V_3, and V_4. In this paper , the values of U_1,

U_3, V_3 and V_4 are adjusted without changing their stability properties, their convergence speed is analyzed, and the security effects of different strategies are studied.

$U_1 = 0$, $V_1 = 50$ means that the safety payoff obtained by both players when they choose strategy S_1 decreases. At this time, the payoff of forced lane-changing vehicles decreases, and they are even less willing to choose forced lane-changing. The speed at which p converges to 0 is accelerated. In the actual driving environment, if the traffic flow is large or the speed is fast, the lane-changing vehicle observes that even if the vehicle behind accepts to give way, the risk of forced lane-changing increases. In this situation, the overall lane-changing traffic flow is more inclined to wait for the lane change. The payoff of accepting to give way becomes smaller for the car coming from behind, and the speed at which q converges to 1 decreases.

$U_3 = 50$, $V_3 = 50$ means that when the two parties choose strategy S_3, the safety payoff decreases due to rear-end collision or impatience caused by deceleration or sudden braking. At this time, the lane-changing vehicle waits for the lane-changing payoff to decrease, and the speed at which p converges to 0 decreases. The payoff of vehicles behind is also reduced due to waiting for lane change, and the speed at which q converges to 1 decreases.

$U_4 = 50$, $V_4 = 0$ means that when the two sides choose strategy S_4, the collision may be caused by the refusal of the vehicle coming from behind to accelerate. At this time, the lane-changing vehicle waits for the lane-changing payoff to decrease, and the speed at which p converges to 0 decreases. However, because the risk of refusing to give way increases, the payoff of choosing to wait to change lanes increases, and the speed at which q converges to 1 increases.

In the actual driving environment, traffic density, distance between front and rear vehicles, speed, and driver impatience will all affect the level of safety payoff. Different levels of payoff will result in different convergence speeds, and reaching a stable state earlier is conducive to smooth and safe driving of traffic flow.

4.2 Evolutionary Stability Analysis Based on Speed Payoff

The speed payoff in normal driving state is 0, and the lane-changing vehicle needs to slow down to enter the ramp. During the game with the following vehicle, if the following vehicle chooses to give way, that is, slow down or stop, and the lane-changing vehicle decelerates or completes the lane change at a constant speed, the lane-changing vehicle and the vehicle behind will lose less speed payoff. When the following vehicle chooses to give way and the lane-changing vehicle chooses to wait for the lane change, both sides lose a large speed payoff. When the vehicle behind chooses to refuse to give way, if the lane-changing vehicle is forced to change lanes, it is likely to cause an accident or both parties stop, and both sides lose a lot of speed and speed payoff. When the lane-changing vehicle chooses to wait for the lane change, it can slow down or stop and wait for the rear vehicle to pass by. The safe distance realizes the lane change, and loses a small speed payoff, while the vehicle behind gains a greater speed payoff.

This paper assumes speed payoff $U_1 = -50$, $U_2 = -150$, $U_3 = -100$, $U_4 = -50$, $V_1 = -50$, $V_2 = -150$, $V_3 = -100$, $V_4 = 100$ (U and V below represent security payoff).

Table 7 Evolutionary stable point based on speed payoff

Equilibrium point	|Jacobi| symbol	tr(Jacobi) symbol	Equilibrium type
(0, 0)	+	−	Stable point ESS
(0, 1)	+	+	unstable point
(1, 0)	+	+	unstable point
(1, 1)	+	−	Stable point ESS
(p*, q*)	+	0	center point

(1) Analysis of evolution process

According to the dynamic evolution process of speed payoff, there are two stable points (0, 0), (1, 1) and equilibrium points (1, 0), (0, 1).

When $U_{fc} = U_{wc}$, $q = q^*$. When $q > q^*$, $U_{fc} > U_{wc}$. When $q > q^*$, the payoff of forced lane change is greater than the payoff of waiting for lane change. When the proportion of the risky driving style group that refuses to give way becomes smaller, that is, when $q < q^*$, the lane-changing vehicles tend to choose to wait for the lane-changing. When $p < p^*$, the payoff of refusing to yield is greater than the payoff of accepting to give way, and the overall traffic flow will choose the strategy of (Wait for the lane change, Refuse togive way) and the evolution tends to $q = 0$, $p = 0$.

When $q < q^*$ and $p > p^*$, the revenue of the lane-changing vehicle waiting for the lane change is greater than the revenue of the lane-changing vehicle forced to change lanes, and the revenue of the vehicle coming from behind is greater than the revenue of refusing, and the initial game strategy between the vehicles is more inclined to (wait for the lane change, accept to give way), in order to achieve overall traffic flow safety and maximum speed payoff, the driver's strategy choice at this time will be different depending on the original data of p and q . When $p > p^*$ and $q < q^*$, in the case of $q/1 - p > q^*/1 - p^*$, (1, 1) is an evolutionary stable point, and when $q/1 - p < q^*/1 - p^*$, (0, 0) is the evolutionary stable point.

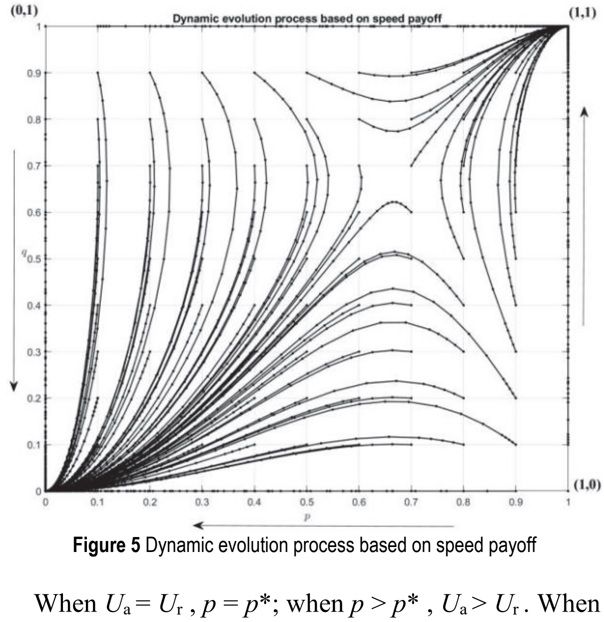


Figure 5 Dynamic evolution process based on speed payoff

When $U_a = U_r$, $p = p^*$; when $p > p^*$, $U_a > U_r$. When $p > p^*$, the revenue of the car coming from behind accepting to give way is greater than the revenue of refusing to yield. $p > p^*$, when $q > q^*$, the payoff of forced lane change is greater than the payoff of waiting for lane change. The overall traffic flow evolution game strategy is biased toward (Change lane compulsorily, Accept to give way) evolution orientation $q = 1$, $p = 1$.

When $p < p^*$, that is, the payoff of the car coming from behind refusing to give way is greater than the payoff of accepting to give way, and when $q > q^*$, the payoff of the forced lane change of the lane-changing vehicle is greater than the payoff of waiting for the lane change. The initial game strategy between vehicles is biased (Change lane compulsorily, Refuse to give way), and accidents are prone to occur at this time, causing traffic jams. In order to optimize the payoff of safety and speed, the driver's strategy will adopt different strategies according to the original data of p and q. When $q > q^*$ and $p < p^*$, when $q - 1/p > q^* - 1/p^*$, (1, 1) is the evolutionary stable point, at $q - 1/p < q^* - 1/$ when p^*, (0, 0) is the evolutionary stable point.

(2) Analysis of evolution speed

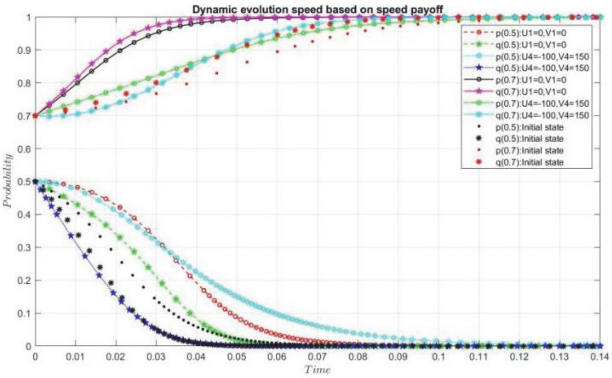


Figure 6 Dynamic evolution speed based on speed payoff

This paper selects (0.5, 0.5) and (0.7, 0.7) as the initial probability, and analyzes the evolution convergence speed under different speed payoffs. It can be seen from Fig. 5 that there are two evolutionary stable points (1, 1) and (0, 0) based on the speed payoff . The stable point is related to U_1, V_1, U_4, and V_4. Adjust the speed payoff without changing the stable point, and study the influence of different speed payoffs on the convergence speed of the stable point.

When $U_1 = V_1 = 0$, that is, the lane-changing vehicle chooses to change lanes compulsorily, and the vehicle behind chooses to give way, the speed of the lane-changing vehicle itself is relatively high, so it can pass smoothly at a uniform speed, and the vehicle behind can also drive safely at a uniform speed. Loss of speed payoff. When $(p, q) = (0.5, 0.5)$, the speed at which the probability of a lane-changing vehicle's forced lane-changing converges to 0 slows down, because the payoff of choosing a forced lane-changing is greater than that of waiting for a lane-changing. At the same time, the speed at which the yield probability of lane-changing vehicles converges to 0 is also slowed down. When $(p, q) = (0.7, 0.7)$, the initial values of p and q are higher, the payoff of choosing strategy 1 becomes larger, and the speed at which the probability of the lane-changing vehicle's forced lane-changing and the rear vehicle's acceptance of lane-changing probability converges to 1 becomes bigger.

When $U_4 = -100$ and $V_4 = 150$, that is, when the lane-changing vehicle chooses to wait for the lane change and the vehicle behind refuses to give way, the lane-changing vehicle needs to wait for more vehicles behind to pass, and loses more time payoff, while the vehicle behind accelerates appropriately Pass, increasing the speed payoff. When $(p, q) = (0.5, 0.5)$, the speed at which p converges to 0 slows down due to the decrease in the payoff of waiting for lane change. On the contrary, the speed at which q converges to 0 becomes larger due to the increase in the payoff of refusing to change lanes. When $(p, q) = (0.7, 0.7)$, since the payoff of the lane-changing vehicle waiting for the lane-changing decreases, the driver chooses to force the lane-changing probability to increase, and the speed at which p converges to 1 increases, while the rear vehicle chooses to accept The ratio of giving way is higher, and the payoff is smaller than that of refusing to give way, so the car behind tends to choose to refuse to give way, and the speed of q converging to 1 is slow, but as time evolves, when p is high, the car behind the game as a whole chooses to accept giving way. The row average utility increases, and the convergence speed of q accelerates.

In the actual lane-changing behavior, due to the different initial speeds and different acceleration and deceleration strategies of the two players in the game, the stable speed of group evolution is also different. The different evolution speeds based on the speed payoff reflect the tendency of the driver to choose a certain strategy by the speed weight value of different strategies. The faster the evolution rate of the evolving stability point, the earlier the group in the game will realize the stable state and achieve the maximum overall utility.

4.3 Evolutionary Stability Based on Comprehensive Payoff

Comprehensive payoff is a comprehensive consideration of safety payoff and speed payoff. Different driving purpose groups on the road have different weights on safety and speed payoff, and driving purposes with higher time requirements have higher weights on speed payoff. In the Change lane compulsorily situation, in order to successfully complete the lane change, the weight of the speed payoff is relatively low, and the driver's main purpose is to complete the lane change safely. Since the car behind is driving in a straight line, it is the group's right not to agree to change lanes, and the weight of speed is relatively high.

Table 8 Evolutionary stable points based on comprehensive payoff

Equilibrium point	|Jacobi| symbol	tr(Jacobi) symbol	Point type
(0, 0)	+	-	Stable point (ESS)
(0, 1)	-	+	uncertain
(1, 0)	+	+	unstable point
(1, 1)	-	-	uncertain
(p^*, q^*)	-	0	center point

(1) Analysis of evolution process

This paper assumes that drivers under normal driving attach equal importance to safety and speed payoff, and the group that needs to change lanes has a higher weight of safety payoff. Assuming that the weight ratio of lane-changing vehicle speed and safety payoff is 3:7, and the weight ratio of rear vehicle speed and safety payoff is 5:5, the typical comprehensive payoff is determined based on the typical safety payoff and typical speed payoff set in the previous two sections. The comprehensive payoff after weighting is $U_1 = 20$, $U_2 = -150$, $U_3 = 40$, $U_4 = 55$; $V_1 = 25$, $V_2 = -150$, $V_3 = 0$, $V_4 = 75$.

Actors who make lane-changing decisions based on comprehensive payoff consider not only safety payoff, but also speed payoff. When the initial probability is (1, 0) , the lane-changing vehicle must choose to change lanes compulsorily and the vehicle behind must choose to refuse to give way. This point is an unstable point, and the lane-changing vehicle has a "mutation", that is, $p < 1$, at this time Mutation strategy -- waiting for lane change payoff is greater than Change lane compulsorily strategy, p will quickly converge to 0. When q "mutates", that is, $q > 0$, and the payoff of the rear vehicle accepting to give way is greater than that of refusing to payoff, q will quickly converge to 1. When the initial probability is (0, 1), the lane-changing vehicle must choose to wait for the lane change, and the vehicle behind must choose to give way. At this time, when the lane-changing vehicle strategy "mutates", that is, $p > 0$, due to the forced lane-changing payoff is less than waiting to change lanes, the mutation strategy will disappear quickly, and p converges to 0. When the vehicle behind "mutates", $q < 1$, because the payoff of refusing to give way is greater than that of waiting to give way, q will quickly converge to 0.

At each equilibrium point, if both sides of the game "mutate" at the same time, they will eventually converge to (0, 0). When $p > 0.3$, the vehicles in the rear choose to change lanes compulsorily due to more lane-changing vehicles. In order to ensure the payoff, the vehicles behind will choose to give way first, and the vehicles that change lanes face the two different strategies of the vehicles behind, and wait for the payoff of changing lanes is always greater than the payoff of Change lane compulsorily, so q first increases and then converges to 0.

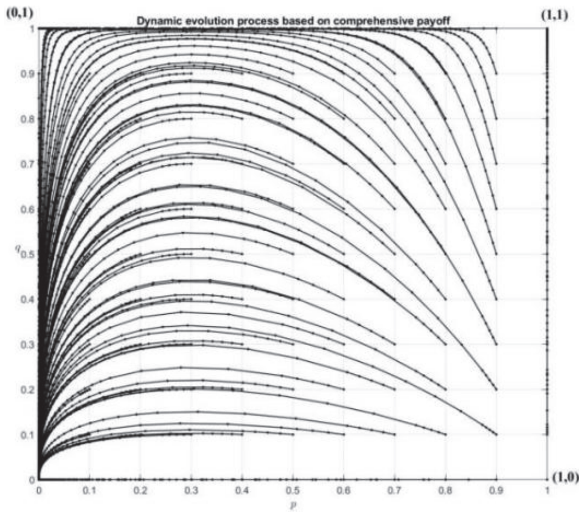


Figure 7 Dynamic evolution process based on comprehensive payoff

The dynamic evolution process and results based on comprehensive payoff are not only affected by safety and speed payoff, but also by the weights of different groups.

(2) Evolution process under different weights

Picture (1) shows the situation that the speed payoff and safety gain of the lane-changing car and the rear car are both 3:7. In this case, because the speed weight of the following vehicle decreases, the payoff of choosing to give way becomes larger. Compared with the typical state in Fig. 4, the speed at which q converges to 0 becomes faster, and (0, 0) is still a stable point. But the turning point of change of q in Fig. 1 is different from that in Fig. 4. When the safety weight of the vehicle behind increases, it will ensure that the probability of forced lane changing strategy is smaller and then increase the probability of refusing to give way.

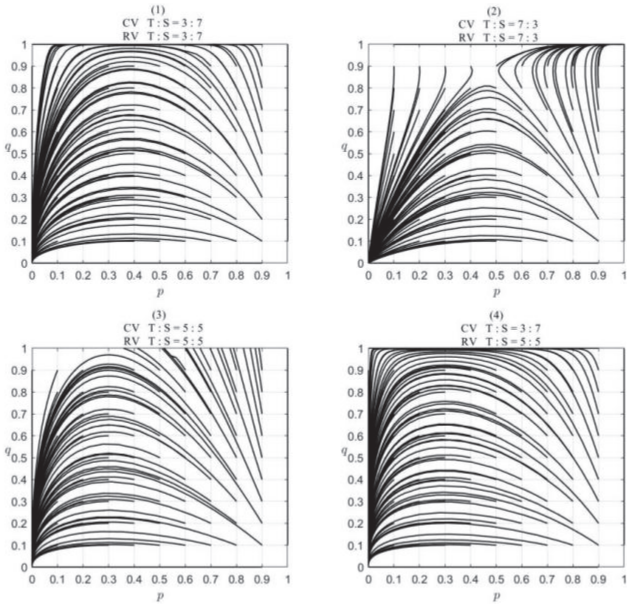


Figure 8 The evolution process of comprehensive payoff based on different weights

Fig. 2 shows the situation that the speed payoff and safety gain of the lane-changing car and the rear car are both 7:3. At this time, both sides of the game pay more attention to the speed payoff, and the evolution dynamic process is similar to the evolution process based on the speed payoff, and there are two evolutionary stable points (0, 0) and (1, 1).

Fig. 3 shows the situation that the speed payoff and safety gain of the lane-changing car and the rear car are both 5:5. In this case, since $U_1 = U_3$ and $q = 1$, p can take any value, so there are multiple stable points (p^*, 1) in the evolution process, and the rest points converge to (0, 0).

Through a comprehensive analysis of the payoff of speed and safety under different weights, the study found that the evolutionary stability point of different groups depends on the importance of speed or safety to the group. The attitude of human drivers towards safety or speed may change every moment in the dynamic behavior of driving, but the demand for traffic safety has a higher priority in the driver's position and the public position. In the situation of forced lane changing such as exiting the turn, the lane changing vehicle has higher requirements for safe lane changing, while the safety weight of the through vehicle is relatively lower than that of the exiting vehicle.

In the process of group evolution, the speed of group evolution reflects to a certain extent the degree of change in the probability of a decision maker choosing a decision. As shown in the Fig. 1, since the rear vehicles pay more attention to safety payoff, the convergence speed of the group's probability of refusing to give way is accelerated. As a single vehicle behind, it reflects that the probability of its choice of refusing to give way increases, compared with individual vehicles changing lanes. The choice of strategy is critical. In the future, the penetration rate of connected cars and even unmanned cars will gradually increase. The driver's license will independently set different driving goals, needs and expectations, and the weight of each goal. After calculation and processing by the central system, the strategy set at the evolutionary stable point will be used as the game behavior probability, greatly improve driving safety and overall traffic speed.

5 RESULTS AND ANALYSIS OF SUMO SIMULATION EXPERIMENT

5.1 Construction of Simulation Platform

SUMO is a microscopic traffic simulation software, which can simulate vehicles with different lane-changing strategies by setting parameters such as driver patience value and cooperative lane-changing value. Due to the complexity of the real traffic environment and some limitations of the evolution model, when $U(S_i) > \Sigma U(S)/n$, that is, the payoff of an individual choosing the strategy S_i is greater than the overall average payoff, its fitness is positive, and the probability of choosing this strategy becomes larger. When $U(S_i) < \Sigma U(S)/n$, the probability decreases. When $U(S_i) = \Sigma U(S)/n$, the probability tends to be stable.

1) Experimental procedure

Step 1: Take the probability p and q as the selection probability of vehicle lane change strategy and rear vehicle strategy, and put c vehicles in total, of which a are off ramp vehicles.

Step 2: Calculate two types of overall average payoff. (including speed payoff and safety payoff)

Step 3: Compare the payoff of each strategy with the corresponding overall average payoff.

Step 4: The strategy with positive fitness increases by a certain proportion, the strategy with negative fitness decreases by a certain proportion, and the strategy with zero fitness remains unchanged.

Step 5: Repeat steps 1-4 until the system reaches a stable state.

2) Parameters and assumptions of the experiment

In SUMO, parameters such as lcCooperative, lcStrategic, lcAssertive, and Impatience of driver can be set to adjust behaviors such as forced lane change of lane-changing vehicles or refusal to give way of rear vehicle. *DRAC* parameter can be set to capture the conflict at the time of lane change. For the case of a crossing, the *DRAC* is defined when the expected time for the first vehicle A to leave the conflict area is greater than the linearly extrapolated time for the second vehicle B to enter the conflict area. When this value is chosen, continuous deceleration at the corresponding rate means that B enters the conflict zone at exactly the time that vehicle A leaves the conflict zone.

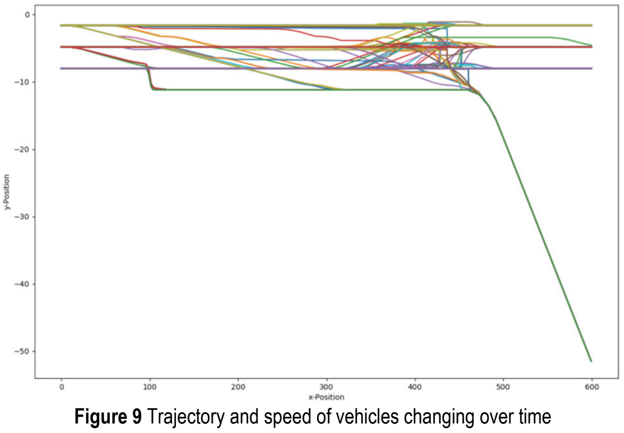


Figure 9 Trajectory and speed of vehicles changing over time

The road network is set as three lanes according to the design standard of urban expressway, and the diversion area and off-ramp lane are added. The traffic flow is 1800 pcu/h, and about 26 out of every 100 vehicles will choose to change lanes [20, 21]. Multiple entrance and exit detectors are placed in the diversion area and SSM devices are installed on the vehicle body to obtain vehicle speed, max*DRAC* and other datas. The trajectory of the vehicle over time is shown in Fig. 9.

5.2 Analysis of Simulation Results

(1) Group payoff simulation

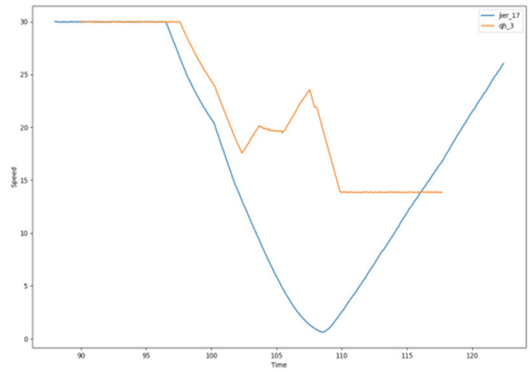
The simulation results show that the speed changes of both sides of the game are different under different strategy combinations. In strategy (1), the forced lane-changing vehicle is selected to play a game with the yielding vehicle, and the deceleration range of the yielding vehicle is greater than that of the lane-changing vehicle. In strategy (2), because forced lane change and refusal to give way are easy to cause accidents, both lane-changing vehicles and rear vehicles have a deceleration process, but lane-changing vehicles have a long stopping phenomenon due to the limitation of the distance from the entrance to the off-ramp. In the strategy (3), when the vehicles waiting to change lanes and the vehicles accepting to give way play the game, both sides have a large deceleration at the same time in order to ensure traffic safety. In strategy (4), the vehicles waiting for lane change and the vehicles refusing to give way slow down at the same time to ensure safety, but the vehicles waiting for lane change stop for a shorter time due to the refusal of the following vehicle.

The speed change of single-vehicle game affects the speed distribution of the whole group. When $p = q = 0.5$, the stop and uniform deceleration phenomena of the forced lane-changing group are more balanced, while the waiting lane-changing group generally decelerates first when it meets the group of vehicles that accept to give way in the game, and then chooses to accelerate or decelerate depending on whether the rear vehicle gives way or not. When it is uncertain, the stop phenomenon will occur. Therefore, fluctuations occur during deceleration. The number of stops and the deceleration range of vehicles accepting to give way are significantly greater than those refusing to give way.

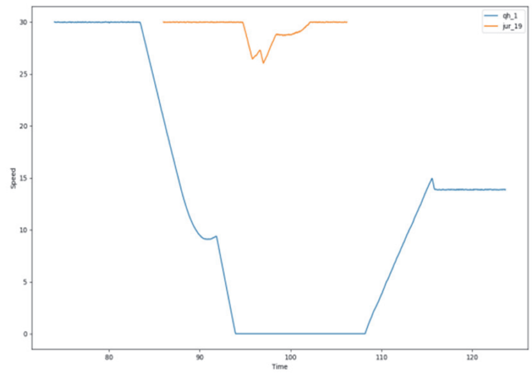
Through simulation and data acquisition, the average speed of the whole group and the number of conflicts are obtained, and the distribution of the population is updated, which verifies the effectiveness of the equilibrium point of the evolutionary game model. Based on the evolutionary game model, the speed payoff, safety payoff and comprehensive payoffs can be significantly improved. The initial distribution of forced lane-changing and accepting give-way is set as two groups when considering speed payoff. Group A: $p = 0.5$, $q = 0.5$; Group B: $p = 0.7$, $q = 0.7$. The simulation results show that the stable point of group A is (0, 0), and the population speed is increased by 8.3% after 45 evolution iterations in the evolution process towards the stable point. The evolutionary stable point of group B is (1, 1), and after 50 evolutionary iterations, the population speed increases by 4.4%.

The initial distribution is set to $p = 0.5$ and $q = 0.5$ when the safety factor is used as the payoff. Simulations verify the stable point (1, 0) of the assumption, and after 45 iterations of evolution, the potential conflict decreased from 9 per 500 vehicles to 2 per 500 vehicles, and the channel change conflict was reduced to 22% of the initial point.

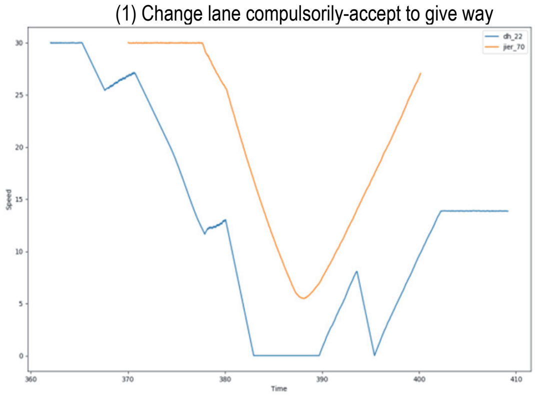
When considering speed payoff and safety payoff comprehensively, different weights of safety and income are set in this paper, and the simulation results clearly show that the comprehensive payoff of speed and safety increases with the number of iterations. The initial distribution is set to $p = 0.5$, $q = 0.5$, and the evolutionary stable point (0, 0) is reached after 45 evolution iterations. The speed has increased by 10.3%, and the number of conflicts has dropped to the initial point, which is 11%. The model can effectively improve the traffic efficiency of intelligent vehicles in the diversion area in the future intelligent network environment, and reduce the risk of accidents.



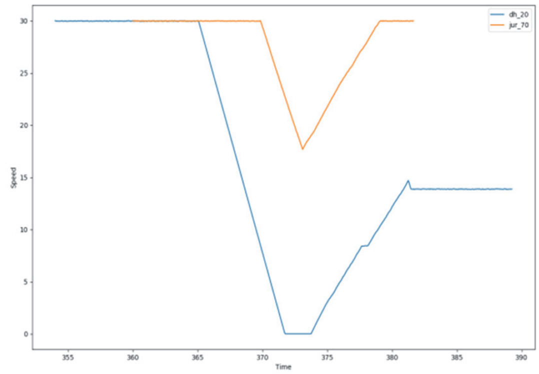
(1) Change lane compulsorily-accept to give way



(2) Change lane compulsorily-refuse to give way

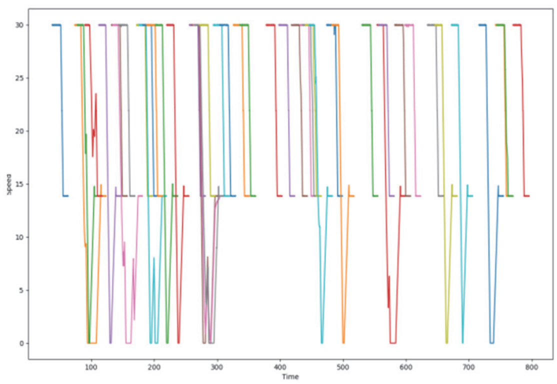


(3) Wait for changing lane-accept to give way

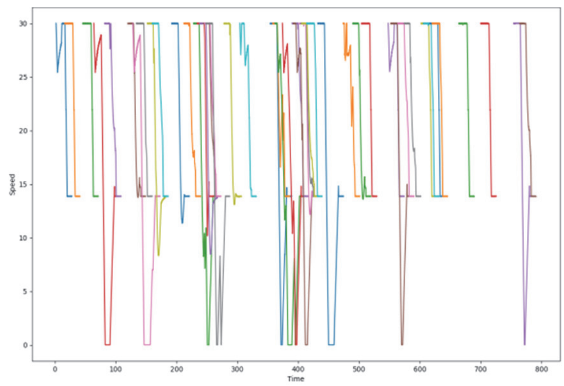


(4) Wait for changing lane-refuse to give way

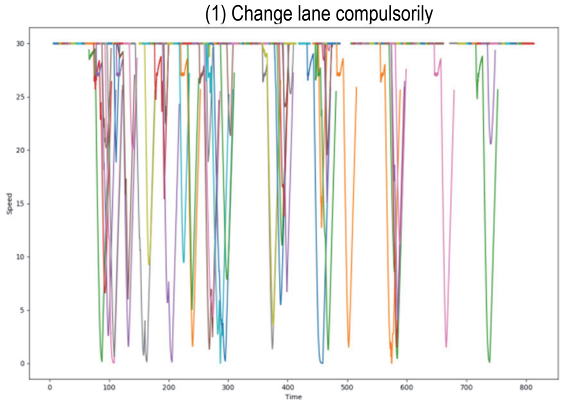
Figure 10 Comparison diagram of vehicle speed during game under different strategies



(1) Change lane compulsorily



(2) Wait for changing lane



(3) Accept to give way

(4) Refuse to give way

Figure 11 Vehicle speed time distribution under different lane change strategies ($p = q = 0.5$)

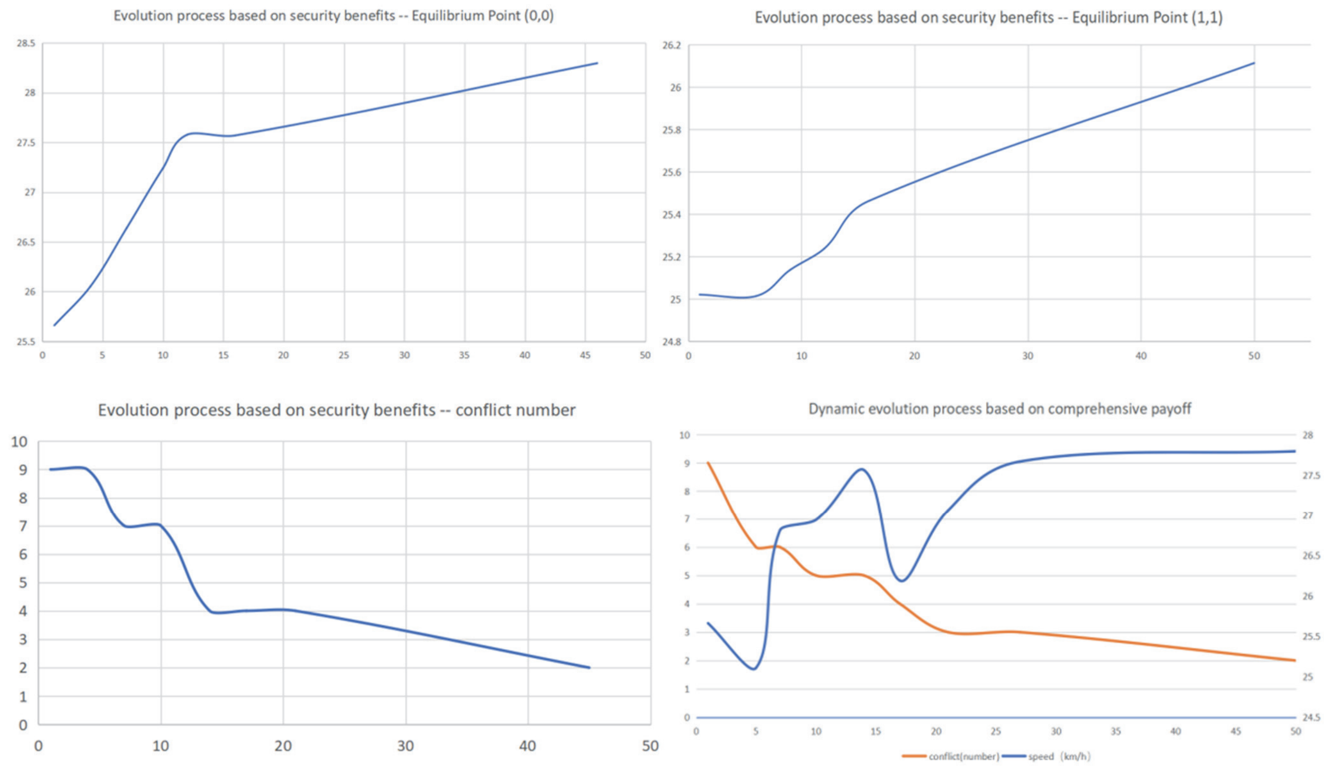
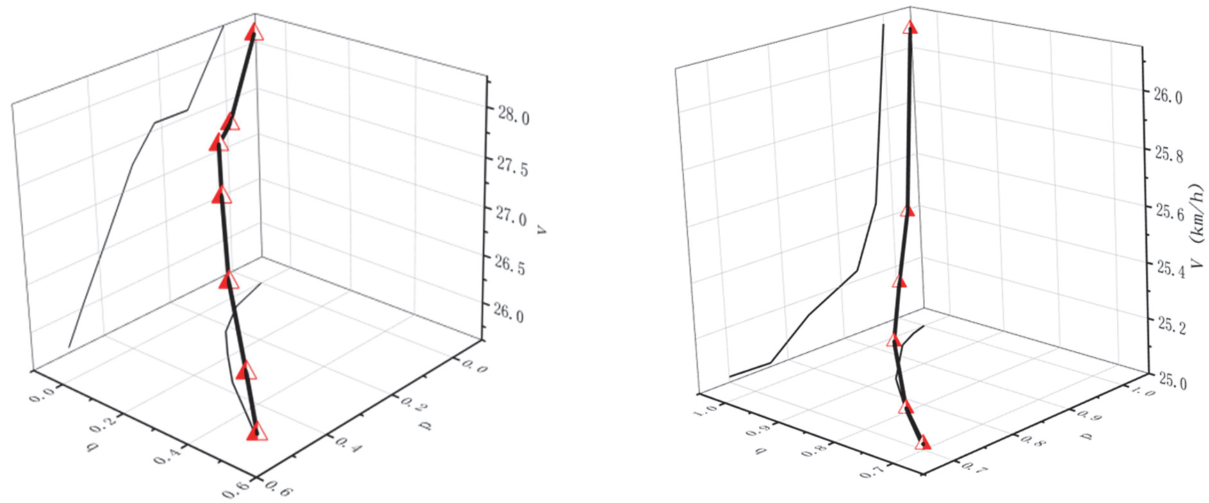
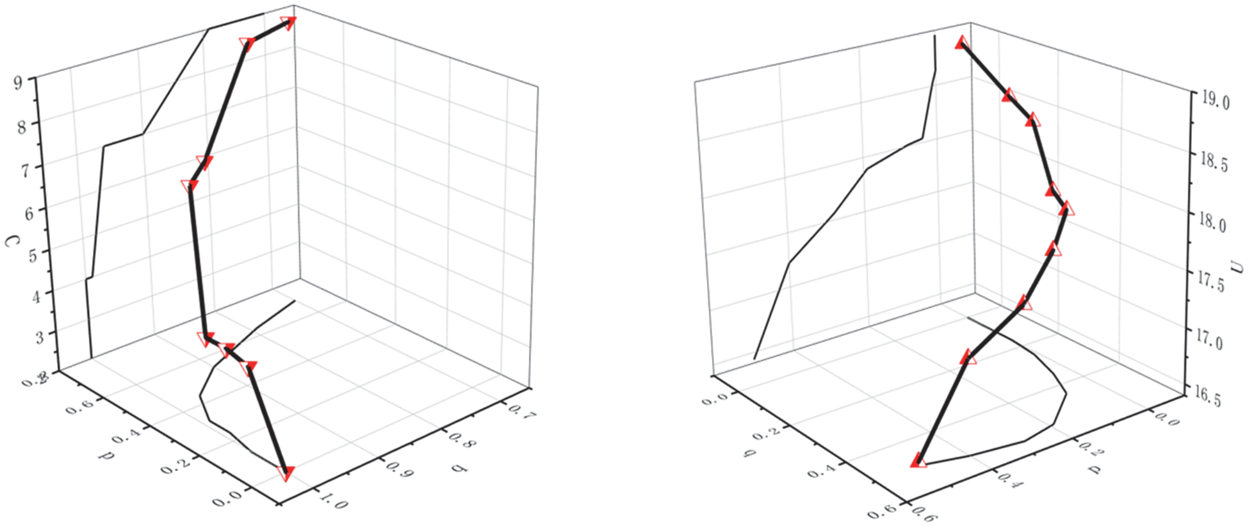


Figure 12 Element iteration process under benefits of different elements



(1) Dynamic evolution process based on speed payoff--(0, 0)

(2) Dynamic evolution process based on security payoff--(1, 1)



(3) Dynamic evolution process based on security payoff--(0, 1)

(4) Dynamic evolution process based on comprehensive payoff--(0, 0)

Figure 13 Evolution process under different factor payoff

6 CONCLUSION

(1) This paper establishes an evolutionary game model of payoff matrix that can reflect the real driving situation of vehicles by analyzing the game behavior in the process of forced lane change when vehicles drive off ramp. By solving the replication dynamic equation, the determinant and trace of Jacobi matrix were calculated, and the stable points under different factor returns were judged. The simulation results show that the returns of evolutionary stable points are better than those of unstable points.

(2) The evolutionary game process reflects the increasing trend of vehicle payoff. When speed is used as payoff, the evolutionary stable points are (0, 0) and (1, 1). Different evolutionary stable points are determined by different strategy distributions on the road. This paper sets two different initial distributions. SUMO simulation shows that the speed of group A increases by 8.3% and that of group B increases by 4.4%. In the case of safety payoff, the conflict of the evolutionary stable point compared with that of the initial distribution is reduced to 22% of the initial point. In the combined payoff of speed and safety, the speed of the evolutionary stable point is increased by 10.3%, and the conflict is reduced to 11% of the initial point.

(3) The game model of lane change in this paper provides a reference for the selection of forced lane-changing strategy of large-scale automatic driving vehicles in the diversion area of urban expressway in the future, realizes the automatic driving under vehicle-road coordination, sets parameters according to the travel purpose and demand, systematically forms a payoff matrix, takes the strategy of evolutionary stable point as the lane-changing strategy in a specific traffic flow, and reduces the number of evolutionary iterations of manual driving. In the future, when the area of intelligent network is realized, the conditional switching area can be unified in the vehicle switching strategy to achieve the maximum overall utility.

(4) The model establishment and simulation experiment in this paper still need to be improved. The judgment of speed and safety payoffs and weights involves human subjectivity and lacks the necessary industry standard support. The SUMO software can reflect the real vehicle simulation condition to a certain extent, and the lane change decision parameters have some limitations. In the future, the real vehicle data set will be used to optimize the lane-changing simulation parameters and modify the lane-changing model.

7 REFERENCE

[1] Hu, L., Tian, H., Zhao. X., Yin, Y., & Ling, H. (2022). Traffic risk evaluation model and application verification of urban expressway exit ramp. *Journal of Safety and the Environment*, *22*(01), 28-35. https://doi.org/10.13637/j.issn.1009-6094.2020.1192

[2] Gipps, P. G. (1986). A model for the structure of lane-changing decisions. *Transportation Research Part B: Methodological*, *20*(5), 403-414. https://doi.org/10.1016/0191-2615(86)90012-3

[3] Ahmed, K. I. (1999). *Modeling drivers' acceleration and lane changing behavior*. Doctoral dissertation, Massachusetts Institute of Technology.

[4] Kita, H., Tanimoto, K., & Fukuyama, K. (2002). A Game Theoretic Analysis of Merging-Giveway InteractionA Joint Estimation Model. *Transportation and Traffic Theory in the 21st Century*, 503-518. https://doi.org/10.1108/9780585474601-025

[5] Talebpour, A., Mahmassani, H. S., & Hamdar, S. H. (2015). Modeling lane-changing behavior in a connected environment: A game theory approach. *Transportation Research Procedia*, *7*, 420-440. https://doi.org/10.1016/j.trpro.2015.06.022

[6] Yang, X., Zhang, S., & Fu, Q. (2015). Research on driving behavior based on game theory. *Highway Traffic Technology*, (07), 105-111. https://doi.org/10.3969/j.issn.1002-0268.2015.07.017

[7] Shang, T., Wu, P., Tang, Bo., Bai, J., & Zhou, L. (2021). Study on the game behavior of vehicle lane changing in the small distance section from tunnel to interchange. *Chinese Journal of Safety Science*, (10), 68-75. https://doi.org/10.16265/j.cnki.issn1003-3033.2021.10.010

[8] Smith, J. M. & Price, G. R. (1973). The logic of animal conflict. *Nature*, *246*(5427), 15-18. https://doi.org/10.1038/246015a0

[9] Pan, W., Xue, Y., Zhao, R., & Lu, W. Z. (2014). Biham Middleton Levine model in consideration of cooperative willingness. *Chinese Physics B*, *23*(5), 058902. https://doi.org/10.1088/1674-1056/23/5/058902

[10] Iwamura, Y. & Tanimoto, J. (2018). Complex traffic flow that allows as well as hampers lane-changing intrinsically contains social-dilemma structures. *Journal of Statistical Mechanics: Theory and Experiment, 2018*(2), 023408. https://doi.org/10.1088/1742-5468/aaa8ff

[11] Jiang, R. (2022). *Evolution of advantageous driving strategies for large-scale autonomous vehicles*. Master's Thesis, University of Chinese Academy of Sciences (Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences). https://doi.org/10.27822/d.cnki.gszxj.2022.000104

[12] Du, X. & Yao, R. (2022). Evolutionary game mechanism of forced lane change of intelligent connected buses. *Journal of Jilin University (Engineering Edition).* https://doi.org/10.13229/j.cnki.jdxbgxb20220207

[13] Lu, J., Li, J., Yuan, Q., & Chen, B. (2019, October). A multi-vehicle cooperative routing method based on evolutionary game theory. *2019 IEEE Intelligent Transportation Systems Conference (ITSC)*, 987-994. https://doi.org/10.1109/ITSC.2019.8917441

[14] Tanimoto, J., Futamata, M., & Tanaka, M. (2020). Automated vehicle control systems need to solve social dilemmas to be disseminated. *Chaos, Solitons & Fractals*, 138, 109861. https://doi.org/10.1016/j.chaos.2020.109861

[15] Wei, L., Cui, Y., & Li, D. (2018). Research on the evolution mechanism of pedestrian and motor vehicle conflict based on evolutionary game theory. *Journal of Physics* (19), 37-49. https://doi.org/10.7498/aps.67.20180534

[16] Chang, S., Shi, J., & Li, X. (2010). Analysis of the behavior process and behavior influencing factors of traffic driving behavior. *Traffic standardization*, (07), 103-107. https://doi.org/10.3869/j.1002-4786.2010.04.006

[17] Hei, K., Qu, D., Guo, H., Jia, Y., & Han Le. (2021). Game behavior and model of connected mixed traffic vehicles. *Science, Technology and Engineering*, (06), 2495-2501. https://doi.org/10.3969/j.issn.1671-1815.2021.06.051

[18] Li, M. & Zhang, J. (2020). Game analysis of driver lane change behavior considering anger. *Chinese Journal of Safety Science*, (02), 165-170. https://doi.org/10.16265/j.cnki.issn1003-3033.2020.02.026

[19] Xue, C., Tan, G., Ding, N., Liu. M., & Du, W. (2017). Collaborative lane switching model of human driving and unmanned driving based on game theory. *Computer Engineering*, (12), 261-266. https://doi.org/10.3969/j.issn.1000-3428.2017.12.047

[20] Knospe, W., Santen, L., Schadschneider, A., & Schreckenberg, M. (2002). Single-vehicle data of highway traffic: Microscopic description of traffic phases. *Physical Review E*, *65*(5), 056-133. https://doi.org/10.1103/PhysRevE.65.056133
[21] Lee, S. E., Olsen, E. C., & Wierwille, W. W. (2004). *A comprehensive examination of naturalistic lane-change*. United States, National Highway Traffic Safety Administration. https://doi.org/10.1037/e733232011-001

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