

## Research Article

# A Study of Taxi Service Mode Choice Based on Evolutionary Game Theory

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Received 27 November 2018; Accepted 11 June 2019; Published 4 July 2019

Academic Editor: Paola Pellegrini

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The emergence of online car-hailing service provides an innovative approach to vehicle booking but has negatively influenced the taxi industry in China. This paper modeled taxi service mode choice based on evolutionary game theory (EGT). The modes included the dispatching and online car-hailing modes. We constructed an EGT framework, including determining the strategies and the payoff matrix. We introduced different behaviors, including taxi company management, driver operation, and passenger choice. This allowed us to model the impact of these behaviors on the evolving process of service mode choice. The results show that adjustments in taxi company, driver, and passenger behaviors impact the evolutionary path and convergence speed of our evolutionary game model. However, it also reveals that, regardless of adjustments, the stable states in the game model remain unchanged. The conclusion provides a basis for studying taxi system operation and management.

## 1. Introduction

Different travel modes, including private cars, public transit, taxis, and subways, play a vital role in modern cities. Research on travel mode choice behavior is a popular subject among traffic and urban planners. In recent decades, emerging technology has led to different service modes appearing within one travel mode.

Recently, as the mobile-internet communication technologies have rapidly developed and popularized, different internet platforms such as Uber, Didi, and Yidao, which can provide the online car-hailing service, appear gradually in China. These platforms provide a preferable booking service and a quick payment system for the passengers by applying an online car-hailing application, which solves the information asymmetry between taxi drivers and passengers effectively. This trip mode is deeply loved by travelers because it does not require passengers to stand on the street to hail a taxi and thus avoids a long waiting time. The rapid growing brings great impact on the traditional taxi mode. The China Internet Network Information Center [1] reported that the total number of online car-hailing in China exceeded 49 million by the 2nd quarter of 2014. Taking Guangzhou, a modern city

in China, as an example, 986 million passenger trips occurred through taxi system in 2015. Among them, the online car-hailing completed 314 million passenger trips (average 0.086 million passenger trips per day), which accounts about 31.7% of the total taxi passenger trips [2]. Based on this, the State Council General Office in China published an important document on 28 July 2016. This document clearly indicated that the taxi market consisted of the traditional taxi mode and the online car-hailing mode [3]. The online car-hailing mode can meet the individualized and diversified trip demands, especially high demands for business population. However, it is pointed that this mode still needs to enhance its service quality and security under the supervision and guidance.

Currently, in China's taxi market, taxi system can provide both the traditional taxi service and the online booking service. The traditional taxi service consisted of the cruising mode and the dispatching mode. The online booking service is only considered as the online car-hailing mode, which mainly includes express car, special car, and ride sharing. Among them, the dispatching service mode is uniformly operated by taxi company. In this mode, by applying telephone or the internet booking system, taxi driver is dispatched to the appointed location to pick up passengers.

The internet booking system helps to achieve the optimum distribution of passenger resources, but it does not complete the connection between individual drivers and passengers. Correspondingly, the online car-hailing mode is managed by platform. In this mode, any individual taxi driver can login to the application used by platform and receives requests for taxi service and finally provides booking service. Today, taxi company has uniformly managed these taxi service modes because of the legalized status of the online car-hailing mode in China. However, the main difference between the dispatching and the online car-hailing modes is that there are expensive contract fees paid by taxi driver to taxi company for the dispatching mode, while these fees are greatly decreased in the latter. Thus, based on these current characteristics of China's taxi system, discussing the choice behaviors which are associated with the dispatching and the online car-hailing taxi service modes is very important.

Many factors influence travel or service mode choices. Geographic characteristics, including density, street design, and land use, impact the choice of travel mode by travelers [4–9]. A public transit network provides preferable services for passengers, leading to stable demand. An underdeveloped public transit system is more likely to increase the demand of private car [10]. Clustered developments with high employment and population densities, as well as balanced jobs and housing opportunities, reduce the probability of automobile use and increase the probability of nonmotorized travel [11]. Higher levels of transportation connectivity, accessibility, and mixed land use contribute to reducing the extent of motorized travel [12]. A study in the Hangzhou, a metropolitan area of China, found that the proportions of bicycle and pedestrian modes are higher in the city centre than in suburb [13]. In addition, many studies have found that the socioeconomic indicators of households and individuals, including income, job status, and car ownership, strongly impact travel mode choice [14, 15].

In addition to the factors listed above, the attitude, motives, and preferences also impact the travel mode choice. For example, people with similar socioeconomic characteristics usually make different travel mode choices because of various attitudes towards traveling [5, 16–19]. Several studies have also shown that special preferences often impact living environment and travel mode choices. For example, people with strong environmental awareness prefer to live in downtown areas, reducing the need of using motorized travel [20–23].

Moreover, the complexity of a trip chain may also be a factor that influences travel mode choice. A trip chain is defined as a travel loop from home to one or more activity locations and back home again [24]. Studies have considered many factors making trip chains complicated. They are the number of activity purposes, location, activity sequence, and frequency [25–29].

Previous studies have focused on the external factors that influence a specific travel mode or traffic system. However, few studies have considered the impact of the travel system's internal factors. For example, the main participants in a certain traffic system, including taxi operators, taxi drivers, and passengers, strongly influence travel and service mode

choices. In addition, most researchers estimated travel mode choice using the perspectives of expected utility theory (EUT) or random utility theory (RUT). However, when focusing on the decision analysis of choice behavior, limited research has been done from the perspective of bounded rationality. Evolutionary game theory (EGT) is a theory that discusses the dynamic evolution of a system in the context of bounded rationality. The theory integrates classical game theory with dynamic analysis to present the evolution of decisions. EGT originated in 1973 with a formalization developed by Smith and Price [30]. EGT mainly focuses on the dynamics of strategy changes, which differs from classical game theory. Thus, EGT can facilitate a better understanding of the evolution of traffic states or decision strategies for traffic managers.

Based on this background, this study explored the dynamic evolution of service mode choice by adopting EGT. Our goal was to explore the evolving state of service mode choice and discuss the impacts of different main participants in taxi system. The approach can support decision-making related to taxi service operation and management.

The contribution of this study on taxi operation and management is in the following ways: (1) The research on modeling choices in taxi system service mode, from the perspective of bounded rationality, has been addressed by few researchers. (2) The study introduced different taxi system stakeholders, as well as initial values and analysis scenarios, to explore their influences through our model. This provides a comprehensive framework to evaluate the model's validity.

The rest of this paper was organized as follows: Section 1 introduced the applied basic theories, including evolutionary dynamics, and replicator dynamics. Section 2 considered two aspects (strategy set identification and payoff matrix determination) and formulates a model framework to analyze the evolutionary process. Section 3 presented the replicator dynamic characteristics and local stability analysis of the service mode choice model, which clearly expresses the dynamic evolving state and equilibrium state of our model. Section 4 introduced three types of influencing factors, including the main participants of the taxi system, parameters, and the initial values and analyzed their impacts on the evolving process. Finally, section 5 presented conclusions.

## 2. Methodology

*2.1. Evolutionary Dynamics and Replicator Dynamics.* Smith [31] proposed the concept of an evolutionary stable strategy (ESS). An ESS is a strategy which is applied by a population in a certain environment and it cannot be invaded by an alternative strategy [32]. The evolutionary stable state is a Nash equilibrium solution. Natural selection is adequate to prevent alternative strategies from invading successfully if population determinatively reaches an ESS. Cressman [33] provided a more detailed definition of ESS.

The characteristic of classical game theory is static, while the characteristic of evolutionary game theory is dynamic. Generally, an evolutionary dynamic model includes two basic elements: a mutation mechanism and a selection mechanism.

TABLE 1: The names and meanings of variables.

Sign	Meaning
$M_1$	Taxi company providing subsidy for taxi driver (Yuan)
$M_2$	The extra paid cost when the passenger choosing the dispatching mode (Yuan)
$M_3$	Taxi company implementing penalty for taxi driver (Yuan)
$x$	The probability that a passenger chooses the dispatching mode
$y$	The probability that a taxi driver provides the dispatching service
$\mu$	The cooperative win-win factor obtained when two players choosing the dispatching mode
$T$	Passenger's profit (Yuan)
$C$	Taxi driver's profit (Yuan)
$S_1$	The strategy space of the passenger
$S_2$	The strategy space of taxi driver
$U_{x1}$	The expected profit resulting from the passenger choosing the dispatching mode (Yuan)
$U_{x2}$	The expected profit resulting from the passenger choosing the online car-hailing mode (Yuan)
$\bar{U}_x$	Average expected profit resulting from the passenger choosing two modes (Yuan)
$U_{y1}$	The expected profit resulting from taxi driver providing the dispatching service (Yuan)
$U_{y2}$	The expected profit resulting from taxi driver providing the online car-hailing service (Yuan)
$\bar{U}_y$	Average expected profit resulting from taxi driver providing two modes (Yuan)

The mutation mechanism provides change, and the selection mechanism selects the strategies with a higher payoff. Moreover, after going through the selection mechanism, those strategies with lower fitness will gradually die out, on the other hand, those with higher fitness survives [34].

ESS assumes that individuals do not control their strategies and do not need to be aware of the game process. To be an ESS, a strategy must be resistant to alternatives. Each ESS corresponds to a Nash equilibrium solution, but not all Nash equilibrium solutions belong to ESS's [32].

**2.2. Formulation of Service Mode Choice Model.** Passengers highly rely on taxi driver who can provide taxi service when they request. This is a bilateral interactive activity. The passenger may choose the dispatching mode or the online car-hailing mode to complete the trip. The taxi driver also selects these two modes to provide taxi service. After repeating choices, a stable state finally forms in practice. This repeated process is an essential dynamic evolution process. Both passengers and drivers have the characteristics of bounded rationality, and information they received is also incomplete. Therefore, based on this analysis, EGT was applied, which usually focuses on the bounded rationality in selections to address the problem in the case study.

In our case, the passenger is considered to be one player in the evolutionary game and taxi driver is the other player. After many repeated games, the final evolutionary stable strategy for two players is presented. In this game process, the dispatching mode and online car-hailing mode are used to establish the game's strategy. Both the passenger and taxi driver take part in the game process in a certain probability distribution. Table 1 presents the parameters and variables in our model.

The step-by-step procedure is described as follows.

*Step 1.* Strategy sets were described. It is assumed that both passengers and taxi drivers are direct participants, and taxi

driver behavior must be managed by taxi company. Here, the passenger ( $k = 1$ ) and taxi driver ( $k = 2$ ) are two game players. The passenger has two available strategies: selecting the dispatching service ( $i = 1$ ) and the online car-hailing service ( $i = 2$ ). Taxi driver has also two available strategies: providing a dispatching service ( $i = 1$ ) and an online car-hailing service ( $i = 2$ ). This strategy set is expressed as  $s = \{s_i^k\} = \{(s_1^1, s_2^1), (s_1^2, s_2^2)\}$ . In addition, the probability of dispatching strategy selected by passengers is  $s_1^1 = x$  ( $x \in [0, 1]$ ). The probability of the online car-hailing strategy is  $s_2^1 = 1 - x$  ( $x \in [0, 1]$ ). The probability that taxi driver provides the dispatching service is  $s_1^2 = y$  ( $y \in [0, 1]$ ), while the probability of the online car-hailing strategy is  $s_2^2 = 1 - y$  ( $y \in [0, 1]$ ).

Moreover, taxi company's management behavior was discussed. In China, taxi market is regulated by the government because of price fairness and security. Taxi company which follows the guiding route of government is responsible for operating taxi market. Thus, taxi driver is directly managed by taxi company. Once taxi driver chooses the dispatching mode, taxi company often supports this choice because it can obtain expensive benefits. However, taxi company is not willing to accept the online car-hailing mode, because of little benefits. Taxi company's management behavior is reflected by applying the subsidy or penalty. Specifically, taxi company supports taxi driver to operate the dispatching mode; the corresponding subsidy is treated as  $M_1$ . Taxi company discourages taxi driver to provide the online car-hailing service mode; the penalty is  $M_3$ .

Finally, the meaning of the cooperative win-win factor is explained. When both the passenger and taxi driver choose the dispatching mode, the greater market share brings more benefits for taxi company, which makes taxi company improve taxi service quality. In addition to achieving trip purpose, the passenger obtains extra benefits, such as a comfortable ride environment and a shorter waiting time. For

TABLE 2: Payoff matrix under different decision conditions.

Strategies		Taxi driver	
		Dispatching mode ( $y$ )	Online car-hailing mode ( $1-y$ )
Passenger	Dispatching mode ( $x$ )	$((1+\mu)T, (1+\mu)C + M_1)$	$(T - M_2, C + M_2 - M_3)$
	Online car-hailing mode ( $1-x$ )	$(0, M_1)$	$(T, C - M_3)$

taxi driver, extra benefits are in the increasing dispatching orders. Thus, this factor denotes the extra benefits.

*Step 2.* We determined the payoff matrix. The payoff for each player is as follows:

(1) The passenger chooses the dispatching mode, while taxi driver provides the dispatching service: the payoff for the passenger is  $(1+\mu)T$ , and the payoff for taxi driver is  $(1+\mu)C + M_1$ ;

(2) The passenger chooses the dispatching mode, while taxi driver provides the online car-hailing service: the payoff for the passenger is  $T - M_2$ , and the payoff for taxi company is  $C + M_2 - M_3$ ;

(3) The passenger selects the online car-hailing mode, while taxi driver provides the dispatching service: the payoff for the passenger is 0 (because of the high-level status of online car-hailing mode), and the payoff for taxi driver is  $M_1$ ;

(4) The passenger selects the online car-hailing mode, while taxi driver provides the online car-hailing service: the payoff for the passenger is  $T$ , and the payoff for taxi driver is  $C - M_3$ .

Table 2 presents the payoff matrix of the two players under interactional situations.

*Step 3.* We constructed the evolutionary game model and developed its game tree.

The evolutionary game model can be expressed as

Players: Passenger, Taxi driver

$$\text{Strategy set: } s = \{s_i^k\} = \{(s_1^1, s_2^1), (s_1^2, s_2^2)\}. \quad (1)$$

Payoff matrix: see Table 2.

*Step 4.* We analyzed the dynamic evolving process of the problem in the case study and illustrated the evolutionary route and equilibrium status.

### 3. Dynamic Evolving Analysis

*3.1. Replicator Dynamics Analysis.* For the passenger player, there are two payoffs of the dispatching strategy. The first payoff is obtained when both the passenger and taxi driver choose the dispatching strategy. The second payoff is produced when the passenger chooses the dispatching strategy, but the taxi driver provides the online car-hailing service. In addition, according to the same principle, the payoff from the

online car-hailing strategy is also obtained. Parameters  $U_{xD}$  and  $U_{xO}$  are represented as follows:

$$U_{xD} = y(1+\mu)T + (1-y)(T - M_2) \quad (2)$$

$$U_{xO} = y \times 0 + (1-y) \times T \quad (3)$$

In the expression,  $U_{xD}$  denotes the payoff of the dispatching strategy, and  $U_{xO}$  denotes the payoff of the online car-hailing strategy. The average payoff of the two strategies is expressed as

$$\begin{aligned} \bar{U}_x &= xU_{xD} + (1-x)U_{xO} \\ &= xyT(1+\mu) + x(1-y)(T - M_2) \\ &\quad + (1-x)(1-y)T \end{aligned} \quad (4)$$

In (4),  $\bar{U}_x$  denotes the average payoff of the two strategies for the passenger.

For the taxi driver player, the payoffs of the two strategies are presented in the following, respectively:

$$\begin{aligned} U_{yD} &= x[(1+\mu)C + M_1] + (1-x)M_1 \\ &= Cx(1+\mu) + M_1 \end{aligned} \quad (5)$$

$$\begin{aligned} U_{yO} &= x(C + M_2 - M_3) + (1-x)(C - M_3) \\ &= xM_2 - M_3 + C \end{aligned} \quad (6)$$

In these expressions,  $U_{yD}$  shows the payoff of the dispatching strategy, and  $U_{yO}$  shows the payoff of the online car-hailing strategy.

Likewise, the average payoff of the two different strategies is expressed as

$$\begin{aligned} \bar{U}_y &= yU_{yD} + (1-y)U_{yO} \\ &= y[Cx(1+\mu) + M_1] + (1-y)(xM_2 - M_3 + C) \end{aligned} \quad (7)$$

In this expression,  $\bar{U}_y$  shows the average payoff of the two strategies for taxi drivers.

In EGT, the core of evolutionary analysis is to discuss how the probability changes when one side of the game changes dynamically. The learning ability of a player, which is usually reflected by the replicator dynamic characteristic, determines the dynamic change rate. Thus, we research the respective replicator dynamics for two players, such as the passenger and taxi driver.

For the passenger, the replicator dynamics of the dispatching strategy is

$$G(x) = \frac{dx}{dt} = x(U_{xD} - \bar{U}_x) \quad (8)$$

$$= x(1-x)[(T + T\mu + M_2)y - M_2]$$

For taxi driver, the replicator dynamics of the dispatching strategy is

$$G(y) = \frac{dy}{dt} = y(U_{yD} - \bar{U}_y) \quad (9)$$

$$= y(1-y)[(C + C\mu - M_2)x + M_1 + M_3 - C]$$

According to EGT, a fixed point of the replicator dynamics is considered as the point at which the equation satisfies optimal solutions. This fixed point describes the situation in which there is no evolution. Thus, a combined equation shown in (10) is used to describe the dynamic change characteristic of the evolutionary game model.

$$G(x) = \frac{dx}{dt} = x(1-x)[(T + T\mu + M_2)y - M_2] = 0$$

$$G(y) = \frac{dy}{dt} \quad (10)$$

$$= y(1-y)[(C + C\mu - M_2)x + M_1 + M_3 - C]$$

$$= 0$$

$$J = \begin{bmatrix} \frac{\partial G(x)}{\partial x} & \frac{\partial G(x)}{\partial y} \\ \frac{\partial G(y)}{\partial x} & \frac{\partial G(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)[(T + T\mu + M_2)y - M_2] & x(1-x)(T + T\mu + M_2) \\ y(1-y)(C + C\mu - M_2) & (1-2y)[(C + C\mu - M_2)x + M_1 + M_3 - C] \end{bmatrix} \quad (12)$$

The determinant of the Jacobin matrix is

$$\det(J) = \frac{\partial G(x)}{\partial x} \times \frac{\partial G(y)}{\partial y} - \frac{\partial G(x)}{\partial y} \times \frac{\partial G(y)}{\partial x}$$

$$= (1-2x)[(T + T\mu + M_2)y - M_2](1-2y)$$

$$\cdot [(C + C\mu - M_2)x + M_1 + M_3 - C] - x(1-x)$$

$$\cdot (T + T\mu + M_2)y(1-y)(C + C\mu - M_2) \quad (13)$$

The trace of the Jacobin matrix is

$$Tra(J) = \frac{\partial G(x)}{\partial x} + \frac{\partial G(y)}{\partial y}$$

$$= (1-2x)[(T + T\mu + M_2)y - M_2]$$

$$+ (1-2y)[(C + C\mu - M_2)x + M_1 + M_3 - C] \quad (14)$$

After solving this equation, its solutions are expressed as follows:

$$x^* = 0,$$

$$x^* = 1,$$

$$y^* = \frac{M_2}{T + T\mu + M_2} \quad (11)$$

$$y^* = 0,$$

$$y^* = 1,$$

$$x^* = \frac{C - M_1 - M_3}{C + C\mu - M_2}$$

The fixed points of this evolutionary game model include A(0,0), B(0,1), C(1,0), D(1,1), and E( $C - M_1 - M_3 / C + C\mu - M_2$ ,  $M_2 / T + T\mu + M_2$ ). However,  $C - M_1 - M_3 / C + C\mu - M_2$  and  $M_2 / T + T\mu + M_2$  should be bounded between 0 and 1, ensuring the existence of equilibrium point E.

**3.2. Local Stability Analysis.** According to Taylor and Jonker [35], a fixed point is regarded as a strictly stable equilibrium strategy if the eigenvalue of Jacobin matrix has a negative real part for replicator dynamic equations. The Jacobin matrix is then used to discuss the ESS under different evolution paths.

The corresponding Jacobin matrix is

Table 3 shows the determinant and traces results of the equilibrium points.

Table 3 shows that the relationship between parameters needs to be analyzed through different scenarios to judge the corresponding  $\det(J)$ 'sign and  $Tra(J)$ ' sign for each equilibrium point. These results in 3 different scenarios are shown in Table 4.

*In Scenario 1*, taxi company's subsidies are greater than the practical profits (= the profits-taxi company's penalties) obtained by taxi driver, when operating the online car-hailing mode. This often makes taxi driver more inclined to provide dispatching service.

*In Scenario 2*, taxi company's subsidies are less than or equal to the practical profits obtained by taxi driver when providing online car-hailing service. In this case, the stable strategies of both players need to be further determined, based on different impact factors.

*In Scenario 3*, the extra profits (= the extra cost paid by the passenger-taxi company's penalties) obtained by taxi driver when providing the online car-hailing service are greater than

TABLE 3: The determinant and trace results of equilibrium points.

Equilibrium points	det(J)	Tra(J)
A(0,0)	$-M_2(M_1 + M_3 - C)$	$-M_2 + M_1 + M_3 - C$
B(0,1)	$(T + T\mu)[C - (M_1 + M_3)]$	$T + T\mu + C - (M_1 + M_3)$
C(1,0)	$M_2(C\mu - M_2 + M_1 + M_3)$	$M_2 + C\mu - M_2 + M_1 + M_3$
D(1,1)	$(T + T\mu)(C\mu - M_2 + M_1 + M_3)$	$-(C\mu - M_2 + M_1 + M_3) - (T + T\mu)$
E(x*,y*)	$(M_1 + M_3 - C)(C + C\mu - M_2)$	0

TABLE 4: The local stability analysis of 3 different scenarios.

Scenarios	Decision conditions	Points	det(J)	Tra(J)	Results
Scenario 1	$M_1 + M_3 > C$ $C > M_2$	A(0,0)	-	+/-	Instability
		B(0,1)	-	+/-	Instability
		C(1,0)	+	+	Instability
		D(1,1)	+	-	Stability(ESS)
		E(x*,y*)	-	0	saddle point
Scenario 2	$C \geq M_1 + M_3 \geq$ $M_2 - C\mu$	A(0,0)	+	-	Stability (ESS)
		B(0,1)	+	+	Instability
		C(1,0)	+	+	Instability
		D(1,1)	+	-	Stability(ESS)
		E(x*,y*)	-	0	saddle point
Scenario 3	$M_1 + M_3 < M_2 - C\mu$	A(0,0)	+	-	Stability(ESS)
		B(0,1)	+	+	Instability
		C(1,0)	-	+/-	Instability
		D(1,1)	-	+/-	Instability

the ones (= the subsidies from taxi company + the cooperative win-win profits) from the dispatching strategy. In this case, the taxi driver is more inclined to provide the online car-hailing service.

Based on this, Table 4 shows the decision conditions of the 3 different scenarios, as well as their local stability analysis.

Table 4 highlights the following results. Points (0,0) in Scenario 2 and Scenario 3 are the strictly dominant pure strategies; points (1,1) in Scenario 1 and Scenario 2 are additional pure strategies in this case’s dynamic system. All 4 equilibrium points are ESSs. This means that when two players make the same decisions, the game system will evolve towards the stable state, which is at the point  $(x = 0, y = 0)$  or at the point  $(x = 1, y = 1)$ . In Scenarios 1 and 2, when the passenger chooses the dispatching mode, while taxi driver provides the same mode, ESS exists in this system at that moment. In Scenarios 2 and 3, when the passenger chooses the online car-hailing mode, while taxi driver provides the same mode, ESS is also reached.

### 4. Results and Discussions

4.1. *The Introduction of Impact Factors.* The results were highly dependent on the impact factors of the case-specific EGT model. Four aspects were used to present their impacts on the case’s evolving process: the behaviors of main participants in the taxi system, the analysis scenarios, the parameter values, and the initial values of  $(x, y)$ .

Firstly, we identified 3 main participants, based on their roles in the taxi system: taxi company, taxi driver, and passenger. Taxi company manages and supervises the daily operation of taxi system; the taxi driver is responsible for providing the taxi service; the passenger consumes the taxi service. Taxi drivers and the passengers were the two main participants. Their behaviors were used to analyze the impacts. They were also served as the game players in the analysis, and their different behaviors were used to construct the case model. The two parameters  $M_1$  and  $M_3$  were used to discuss company’s management behavior; the profit  $(C)$  was used to discuss the operational behavior for taxi driver; and the profit  $(T)$  was used to analyze the service mode choice for the passenger. In addition, when analyzing the behavior impact of a certain participant, we assumed that the impacts of the other two participants remained unchanged.

Also, by assigning the hypothetical values of the parameters, we applied our models in different numeral scenarios to discuss the evolving case process. These parameters must meet the limits of decision conditions in Scenario 1, Scenario 2, and Scenario 3.

Finally, the initial values of  $(x, y)$  were randomly selected to present their influences on the evolving process. These combinations included  $(0.4, 0.6)$ ,  $(0.3, 0.5)$ ,  $(0.2, 0.8)$ ,  $(0.6, 0.4)$ ,  $(0.8, 0.3)$ ,  $(0.5, 0.2)$ ,  $(0.2, 0.1)$ , and  $(0.1, 0.5)$ . In this analysis, the cooperative win-win factor  $(\mu)$  was set as 0.8, when both the passenger and taxi driver chose the dispatching strategies. Based on this, we applied the replicator dynamic system to

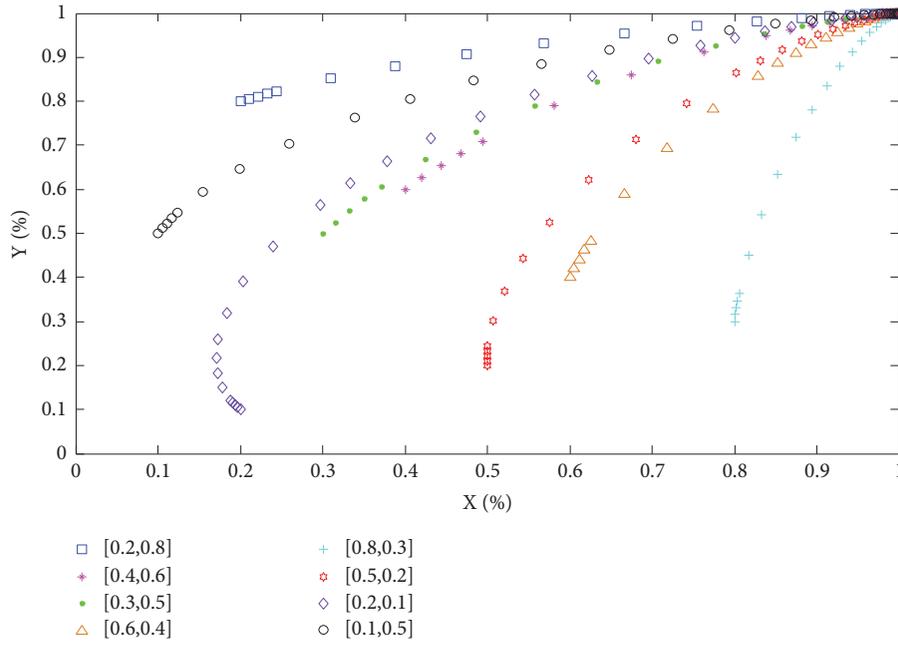


FIGURE 1: The Y-X type of phase diagram (ESS: D(1,1)).

simulate the evolutionary process and thereby demonstrated the validity of our proposed model.

**4.2. The Impact Analysis of Taxi Company's Management Behavior.** In this part, when considering the impact of taxi company's management behavior, the passenger's profit ( $T$ ) was set as 10 and taxi driver's profit ( $C$ ) was set as 15. Based on 3 scenarios in Table 4, the numerical examples of taxi company's subsidies or penalties were provided to present the impact of management strategies on the evolutionary stable state. The simulation domain of time window was  $t \in [0, 5]$ . This study generated three types of phase diagrams: Y-X, X-t, and Y-t. Specially, the Y-X diagram showed the dynamic evolution of the interaction between taxi driver choice behavior and passenger choice behavior. This evolution happened in the  $[0, 1] \times [1, 0]$  space. In the X-t and Y-t diagrams, the probabilities that the passenger and taxi driver, respectively, chose a certain strategy changed as time went by.

*(1) Scenario 1.* In Scenario 1, the parameter relationships must meet the decision conditions  $M_1 + M_3 > C$  and  $C > M_2$ . Taxi company's subsidy ( $M_1$ ) was set as 12, and penalty ( $M_3$ ) was set as 6. The passenger must pay an extra cost ( $M_2$ ) of 5 in the dispatching service.

In Scenario 1, taxi company subsidized taxi driver who provided the dispatching service and penalized taxi driver providing the online car-hailing service. When the subsidies were greater than the profits obtained by taxi driver, both the passenger and taxi driver chose the dispatching mode, which eventually became the stable strategy. At this point, the equilibrium point D(1,1) became the ESS. Figure 1 showed the phase diagram of Y-X type.

Figure 1 illustrated the evolution process and eventual convergence of  $(x,y)$  for different initial values of  $(x,y)$ . In Scenario 1, taxi driver obtained more profits under taxi company management. Taxi driver followed taxi company's policy guidance and gradually adjusted his operating strategy to shift towards the dispatching strategy and actively cooperated with taxi company to implement future industry development. In turn, the passenger increasingly chose the dispatching mode, if the taxi market, which was dominated by the dispatching strategy, gradually became mature. Thus, both the passenger and taxi driver received the best effect of the win-win cooperation, supporting the overall development of the taxi industry eventually.

Figures 2 and 3 illustrated the evolutionary paths of  $(x,y)$ , based on the different initial values of  $(x,y)$  in Scenario 1.

*(2) Scenario 2.* In Scenario 2, the parameter relationships required to meet the following the decision conditions:  $C \geq M_1 + M_3$  and  $M_1 + M_3 \geq M_2 - C\mu$ . Here, the subsidy of taxi company ( $M_1$ ) was set as 10 and the penalty ( $M_3$ ) was set as 4. The passenger must pay an extra cost ( $M_2$ ) of 5.

In Scenario 2, when the subsidies were less than the profits obtained by taxi driver, the strategy which showed that both the passenger and taxi driver chose the online car-hailing mode eventually became the stable state. Unlike Scenario 1, in Scenario 2, taxi driver only obtained lower profits when there was taxi company's management. Thus, taxi driver often selected the online car-hailing strategy, because this strategy could increase driver's interests. This suggested that the development direction expected by taxi company was no longer tracked. At this point, the passenger increasingly chose the online car-hailing mode, and the taxi market eventually became dominated by the online car-hailing strategy. Therefore, this scenario was not conducive to

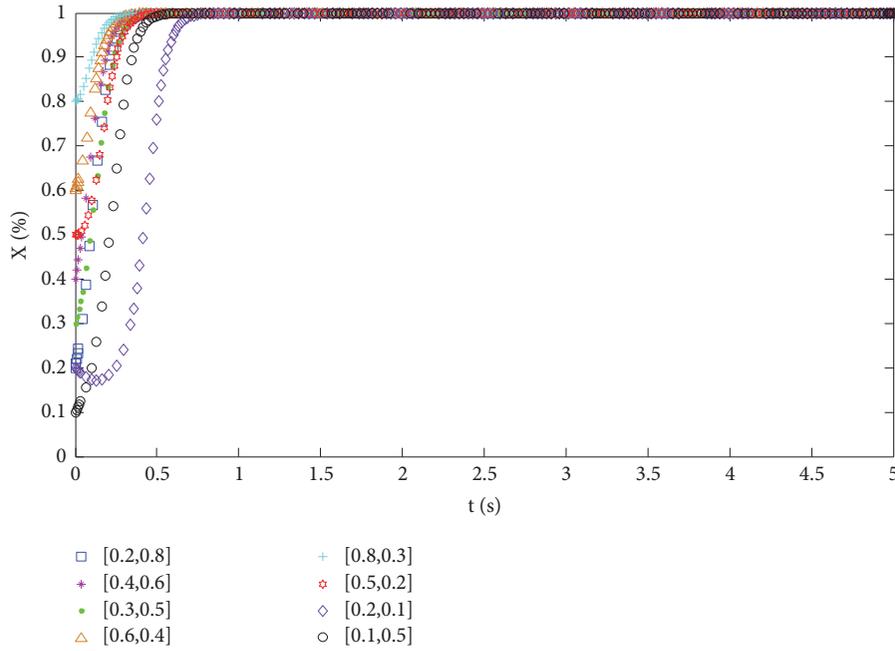


FIGURE 2: The X-t type of phase diagram (ESS: D(1,1)).

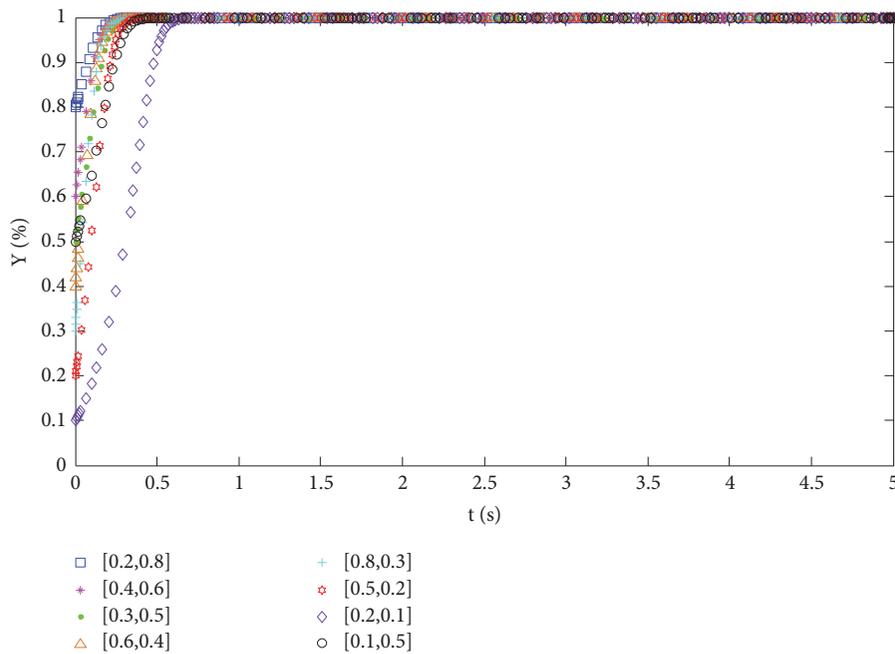


FIGURE 3: The Y-t type of phase diagram (ESS: D(1,1)).

the ideal expectation of taxi company. In addition, once the decision condition of  $M_1 + M_3 \geq M_2 - C\mu$  was established, we found that if taxi company provided more subsidies to taxi driver, including implementing more penalties to taxi driver, they were more likely to choose the online car-hailing strategy; the cooperative win-win factor was also greater and there was a greater probability that the evolutionary model eventually converged at point (1,1). Figure 4 showed the Y-X type of the phase diagram.

Figure 4 indicated the evolution process and eventual convergence of  $(x,y)$  with respect to different initial values of  $(x,y)$ . The figure showed that when the initial values of  $(x,y)$  were treated as (0.2,0.8), (0.4,0.6), (0.3,0.5), (0.6,0.4), (0.8,0.3), (0.5,0.2), and (0.1,0.5); the evolutionary model eventually converged at equilibrium point D(1,1), while (0.2,0.1) was used as the initial value of  $(x,y)$ , the evolutionary model converged at equilibrium point A(0,0). This suggested that the evolutionary state of the two players in the game

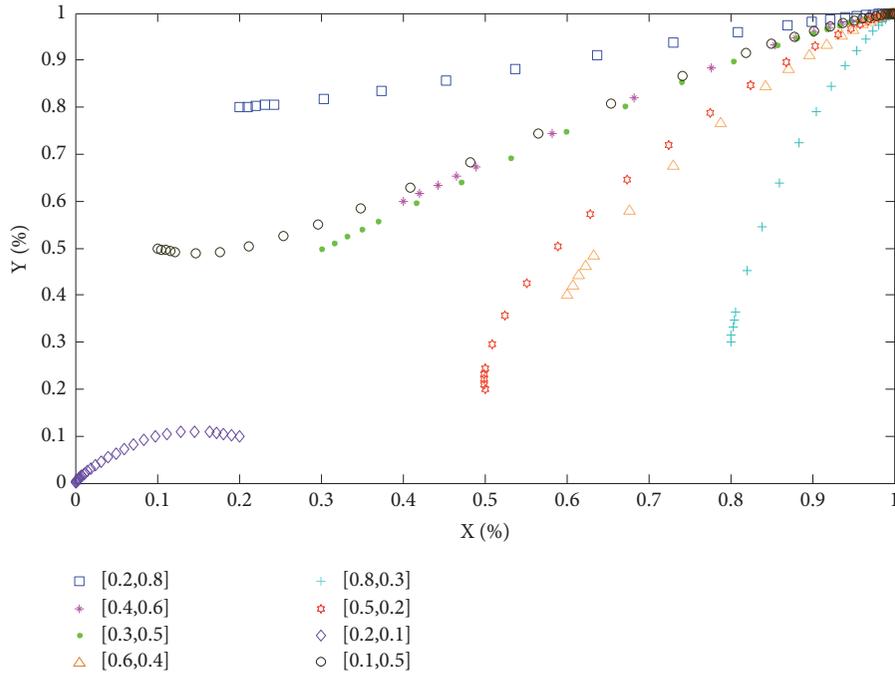


FIGURE 4: The Y-X type of phase diagram (ESS: D(1,1) & A(0,0)).

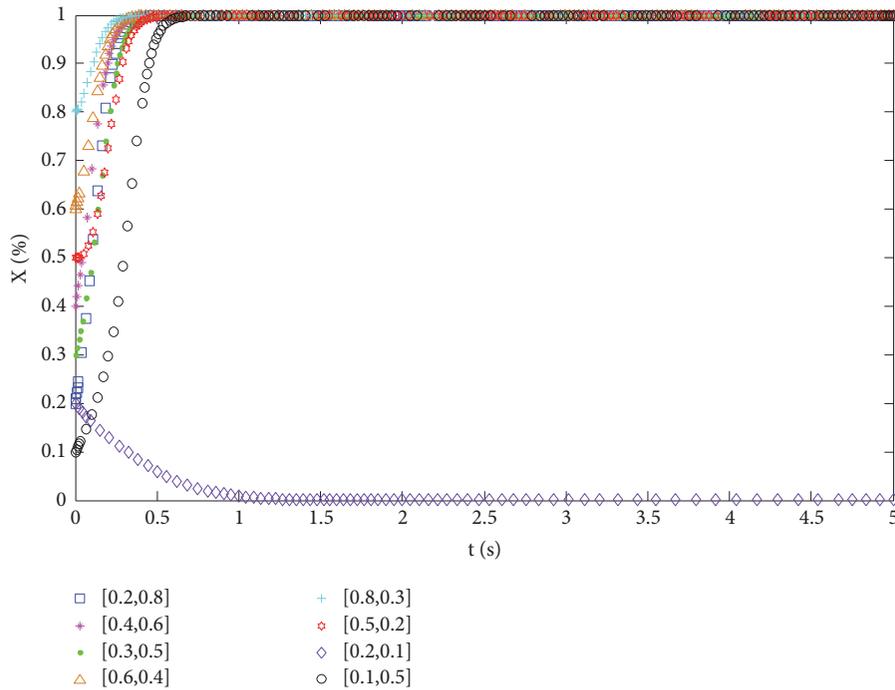


FIGURE 5: The X-t type of phase diagram (ESS: D(1,1) & A(0,0)).

was related to the initial probability if a player chose a certain strategy. The probability that the evolutionary model converged at point A(0,0) would be greater if the initial probabilities that two players chose the online car-hailing strategies were larger.

Figures 5 and 6 illustrated the evolutionary paths of  $(x,y)$  with respect to different initial values of  $(x,y)$  in Scenario 2.

(3) *Scenario 3.* In Scenario 3, the relationships between parameters must meet the following decision condition:  $M_1 + M_3 < M_2 - C\mu$ . The subsidy ( $M_1$ ) and penalty ( $M_3$ ) were set as 4. Passengers should pay an extra cost ( $M_2$ ) of 22 in the taxi market that could not provide the dispatching service. In Scenario 3, the decision condition of  $x^* > 1$  resulted in the disappearance of equilibrium

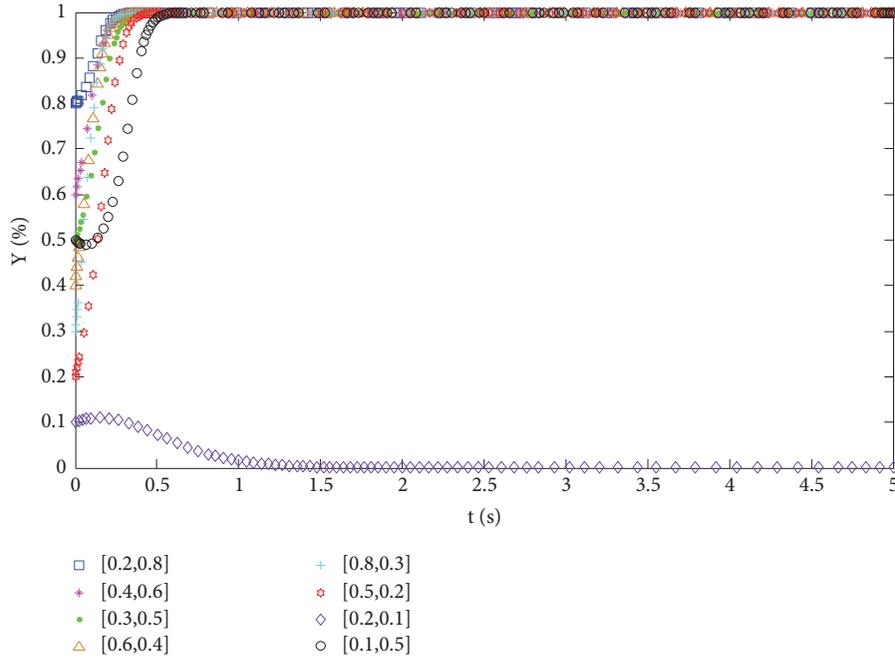


FIGURE 6: The Y-t type of phase diagram (ESS: D(1,1) & A(0,0)).

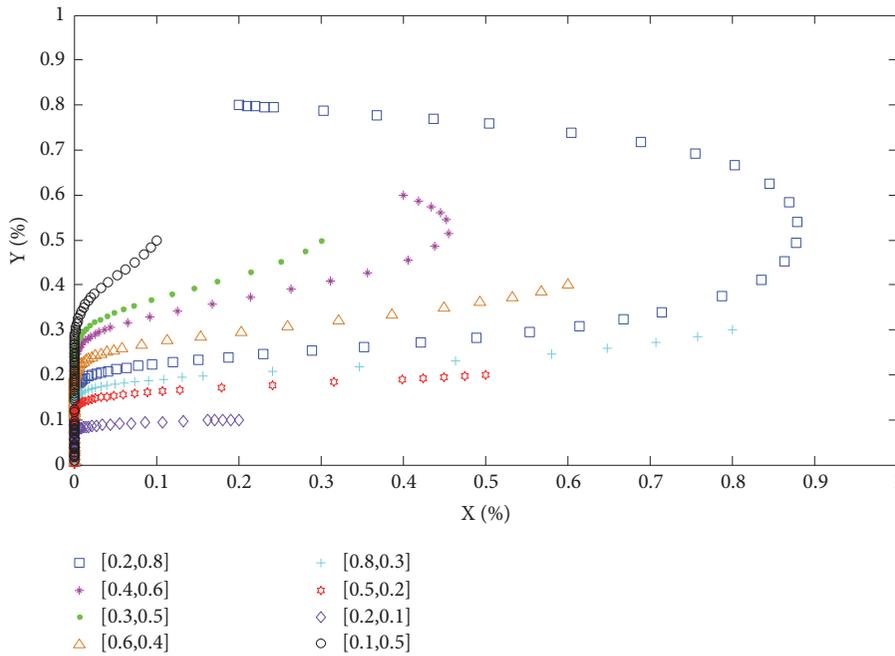


FIGURE 7: The Y-X type of phase diagram (ESS: A(0,0)).

point E. Figure 7 presented the Y-X type of the phase diagram.

Figure 7 showed the evolution process and eventual convergence of  $(x, y)$  with respect to different initial values of  $(x, y)$ . The figure showed that if taxi company provided fewer subsidies to taxi driver and implemented fewer penalties for taxi driver, they would then choose the online car-hailing strategy, and the cooperative win-win factor was also smaller; the probability that  $M_1 + M_3 < M_2 - C\mu$  eventually occurred

was greater as well. The situation in which two players chose the online car-hailing modes eventually became the stable state for the evolutionary system.

Figures 8 and 9 illustrated the evolutionary paths of  $(x, y)$  with respect to different initial values of  $(x, y)$  in Scenario 3.

*4.3. The Impact Analysis of Taxi Driver's Operation Behavior.* In this part, taxi company's subsidy and penalty remained unchanged, and the profit ( $T$ ) of the passenger was set as 10,

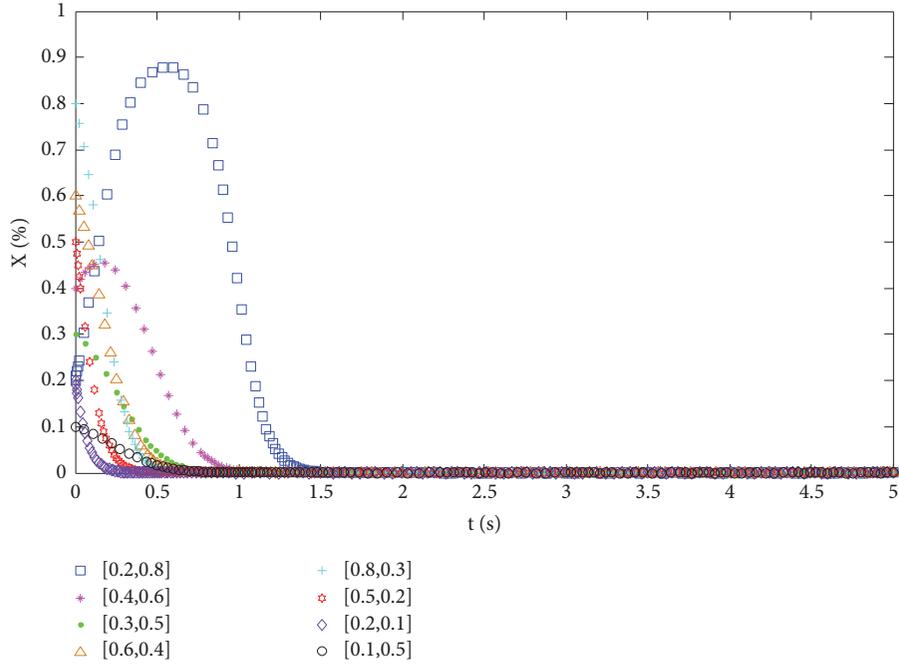


FIGURE 8: The X-t type of phase diagram (ESS: A(0,0)).

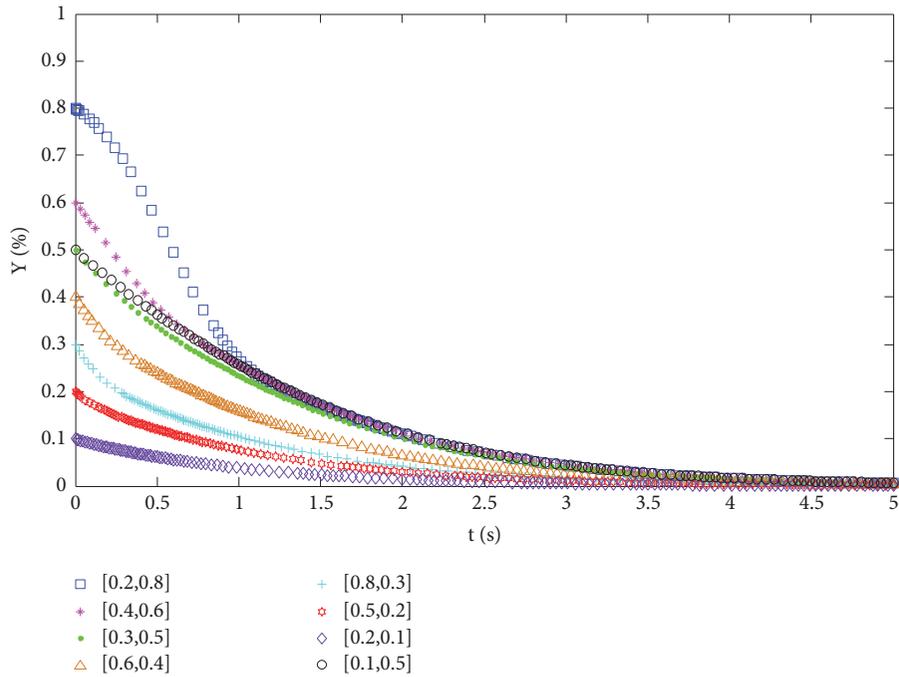


FIGURE 9: The Y-t type of phase diagram (ESS: A(0,0)).

when analyzing the influence of driver’s operation behavior. Based on the 3 scenarios in Table 4, the numerical examples of driver’s profits were provided to illustrate the impact of operational behavior on the evolutionary stable state.

(1) *Scenario 1.* The replicator dynamics in Scenario 1 were expressed as

$$\begin{aligned} G(x) &= x(1-x)(23y-5) = 0 \\ G(y) &= y(1-y)[(1.8C-5)x+18-C] = 0 \end{aligned} \quad (15)$$

According to the decision conditions in Table 4 and the parameters from Scenario 1, we concluded that the range of driver’s profit ( $C$ ) belonged to  $[5, 18]$  Yuan. Figures 10(a) and 10(b) showed the three-dimensional phase diagrams of replicator dynamics, when  $(0.4,0.6)$  and  $(0.3,0.5)$  were chosen as the initial values of  $(x,y)$ , respectively. These two diagrams demonstrated the evolving process of the replicator dynamics system in Eq. (15) with the change of driver’s profit ( $C$ ). Figure 10 described that the replicator dynamics of  $(0.4,0.6)$

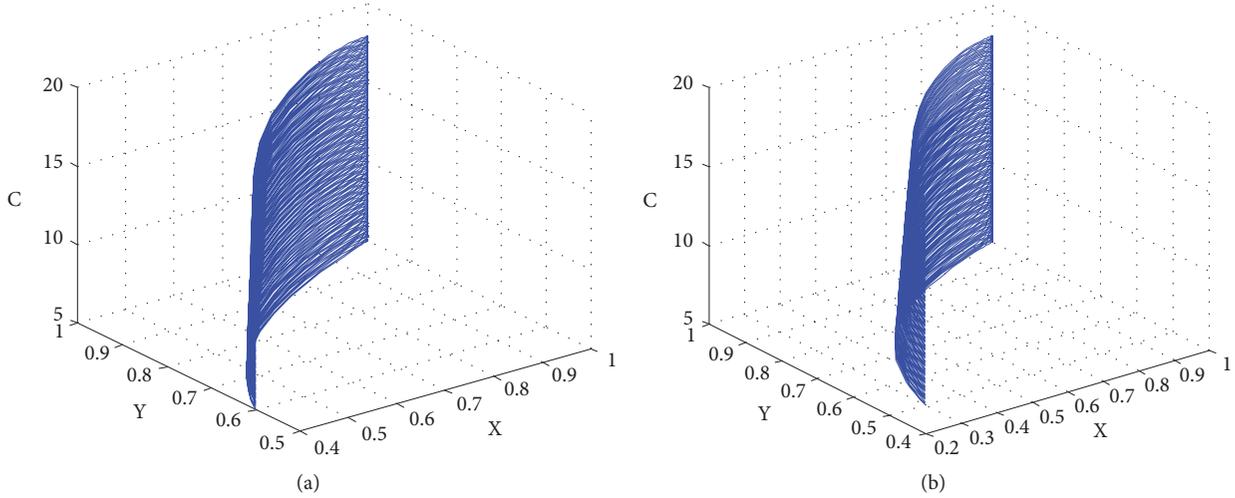


FIGURE 10: The change of C with respect to the initial values of (0.4,0.6) and (0.3,0.5) in Scenario 1.

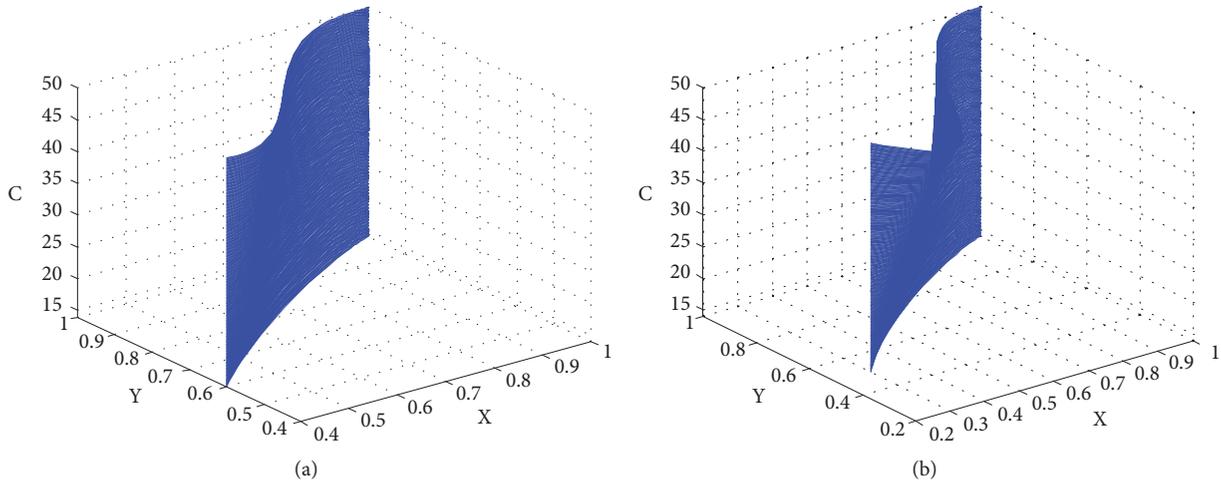


FIGURE 11: The change in C with respect to the initial values of (0.4,0.6) and (0.3,0.5) in Scenario 2.

and (0.3,0.5) eventually stabilized with equilibrium states at point (1,1). This showed that regardless of the initial values of  $(x,y)$  and driver's profit  $(C)$ , the evolutionary systems would eventually stabilize, with the ESS lying at the point  $(x^* = 1, y^* = 1)$ .

(2) *Scenario 2.* The replicator dynamics in Scenario 2 was presented as

$$\begin{aligned} G(x) &= x(1-x)(23y-5) = 0 \\ G(y) &= y(1-y)[(1.8C-5)x+14-C] = 0 \end{aligned} \tag{16}$$

Similarly, based on the decision conditions in Table 4 and the parameters from Scenario 2, we concluded that the range of driver's profit  $(C)$  belonged to  $[14, +\infty]$  Yuan. The profit  $(C)$  ranged from 14 to 50 Yuan. Figures 11(a) and 11(b) depicted the three-dimensional phase diagrams of replicator dynamics system, when (0.4,0.6) and (0.3,0.5) were chosen as the initial values of  $(x,y)$ , respectively. These diagrams

indicated the evolving process of the replicator dynamics system in Eq. (16) with the change in driver's profit  $(C)$ . Figure 11 showed that the replicator dynamics of (0.4,0.6) and (0.3,0.5) eventually became stable and converged at point (1,1). This proved that, regardless of the initial values of  $(x,y)$  and driver's profit  $(C)$ , the systems would eventually stabilize, with an ESS at the point  $(x^* = 1, y^* = 1)$ .

Table 4 showed that, in Scenario 2, both D(1,1) and A(0,0) were ESSs in this evolutionary system. Two different convergence points, (1,1) and (0,0), appeared in this three-dimensional phase diagram of replicator dynamics system. Taxi driver's profit  $(C)$  changed in the range of [14, 50] Yuan; the initial values of  $(x,y)$  were (0.2,0.1) and (0.1,0.5), respectively. The simulation process revealed that the evolutionary system eventually converged at point (1,1), while the profit  $(C)$  changed in the range of [14, 20] Yuan and the initial value of  $(x,y)$  was (0.2,0.1). Figure 12(a) presented this dynamic process. In addition, when  $C$  was in the range of [20, 50] Yuan and the initial value of  $(x,y)$  was (0.2,0.1), ESS was at the point  $(x^* = 0, y^* = 0)$ . This result was described in Figure 12(b).

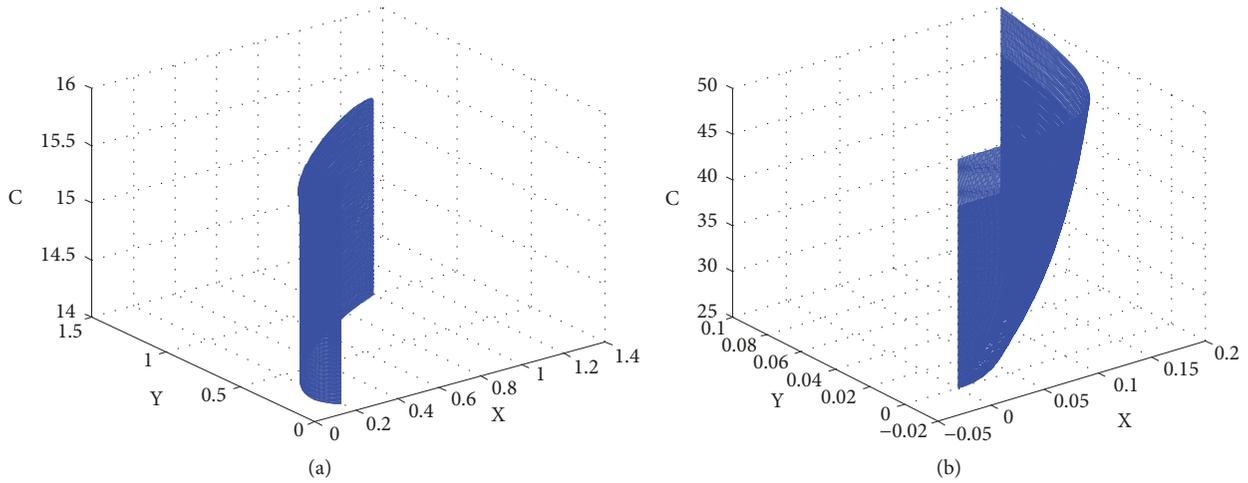


FIGURE 12: The simulation results with respect to the initial value of (0.2,0.1) and  $C \in [14, 50]$  in Scenario 2.

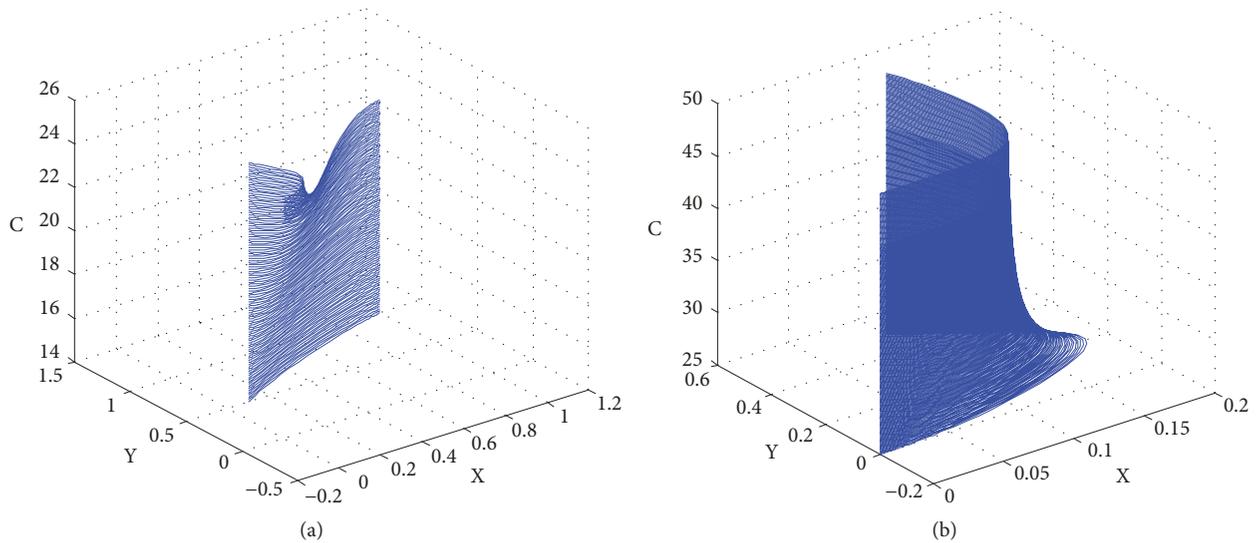


FIGURE 13: The simulation results with respect to the initial value of (0.1,0.5) and  $C \in [14, 50]$  in Scenario 2.

Similarly, the results showed that when the profit ( $C$ ) changed in the range of  $[14, 25]$  Yuan and the initial value of  $(x, y)$  was  $(0.1, 0.5)$ , the evolutionary system eventually converged at point  $(1, 1)$ . This was shown in Figure 13(a). In addition, if  $C$  belonged to the range of  $[25, 50]$  Yuan and the initial value of  $(x, y)$  was  $(0.1, 0.5)$ , the ESS was at the point  $(x^* = 0, y^* = 0)$ . This evolutionary process was described in Figure 13(b).

From Figures 11, 12, and 13, it could be shown that although the analyzed scenarios were the same, the stable strategies were different because of the different initial values of  $(x, y)$  and profits. With the change in the profit ( $C$ ), there were two convergence points in the system. However, it was certain that, regardless of what the changes were, the systems in Scenario 2 still eventually converged at point  $(0, 0)$  or point  $(1, 1)$ . This conformed to the conclusions of Scenario 2 in Table 4.

(3) Scenario 3. The replicator dynamics in Scenario 3 were written as

$$\begin{aligned} G(x) &= x(1-x)(40y-22) = 0 \\ G(y) &= y(1-y)[(1.8C-22)x+8-C] = 0 \end{aligned} \tag{17}$$

Based on the decision conditions in Table 4 and the parameters from Scenario 3, we concluded that the range of driver's profit ( $C$ ) fell within  $[0, 14]$  Yuan. The simulation process concluded that the replicator dynamic system would become disorderly and unsystematic if the profit ( $C$ ) was too small. Thus, The research scope of  $C$  was from 10 to 14 Yuan. Figures 14(a) and 14(b) depicted the three-dimensional phase diagrams of replicator dynamics system, when  $(0.4, 0.6)$  and  $(0.3, 0.5)$  were chosen as the initial values of  $(x, y)$ , respectively. This demonstrated the evolving process of the replicator dynamics system in (17) with the change

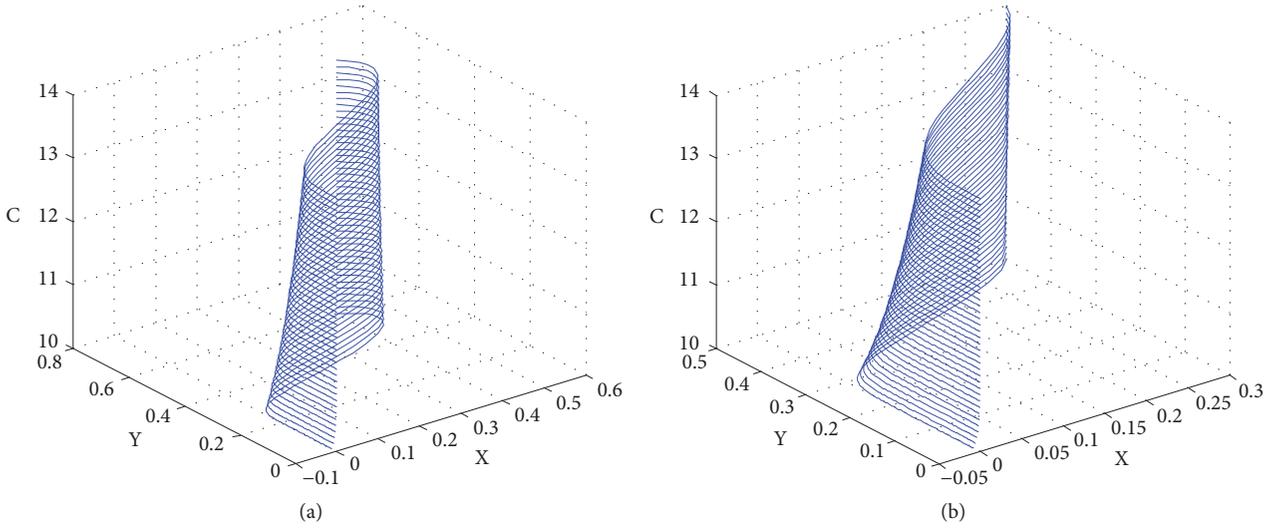


FIGURE 14: The change of  $C$  with respect to the initial values of  $(0.4,0.6)$  and  $(0.3,0.5)$  in Scenario 3.

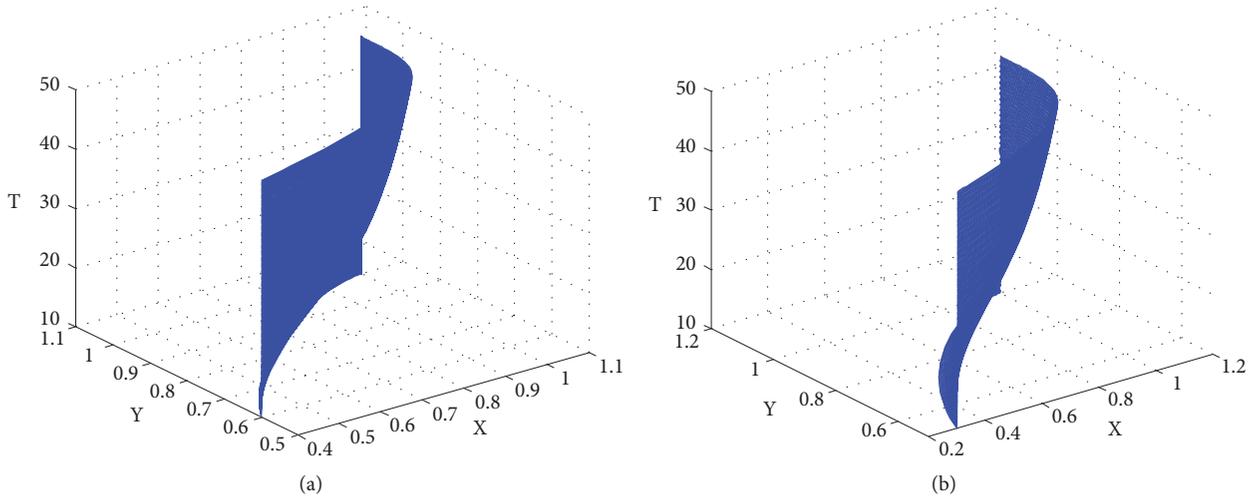


FIGURE 15: The change in  $T$  with respect to the initial values of  $(0.4,0.6)$  and  $(0.3,0.5)$  in Scenario 1.

in driver’s profits ( $C$ ). Figure 14 showed that the replicator dynamics systems of  $(0.4,0.6)$  and  $(0.3,0.5)$  became stable and eventually converged at point  $(0,0)$ . This demonstrated that regardless of the initial values of  $(x,y)$  and driver’s profit ( $C$ ), the systems would eventually stabilize, with an ESS at the point  $(x^* = 0, y^* = 0)$ .

**4.4. The Impact Analysis of Passenger Choice Behavior.** In this part, taxi company’s subsidy and penalty had no change, and the taxi driver’s profit ( $C$ ) was set as 15 Yuan, when discussing the impact of passenger choice behavior. Based on the 3 scenarios in Table 4, the numerical examples of passenger profits were presented to show the impact of service mode choice on the evolutionary stable state.

(1) *Scenario 1.* The replicator dynamics in Scenario 1 were expressed as

$$\begin{aligned} G(x) &= x(1-x)[(1.8T+5)y-5] = 0 \\ G(y) &= y(1-y)(22x+3) = 0 \end{aligned} \tag{18}$$

$T$  ranged from 10 to 50 Yuan. Figures 15(a) and 15(b) showed the three-dimensional phase diagrams of replicator dynamics, when  $(0.4,0.6)$  and  $(0.3,0.5)$  were chosen as the initial values of  $(x,y)$ , respectively. This demonstrated the evolving process of the replicator dynamics system in (18) when the passenger’s profit ( $T$ ) changed. Figure 15 indicated that the replicator dynamics systems of  $(0.4,0.6)$  and  $(0.3,0.5)$  eventually became stable, and their equilibrium states occurred at point  $(1,1)$ . This showed that, regardless of the initial values of  $(x,y)$ , the systems would eventually stabilize with an ESS at the point  $(x^* = 1, y^* = 1)$ .

(2) *Scenario 2.* The replicator dynamics in Scenario 2 were expressed as

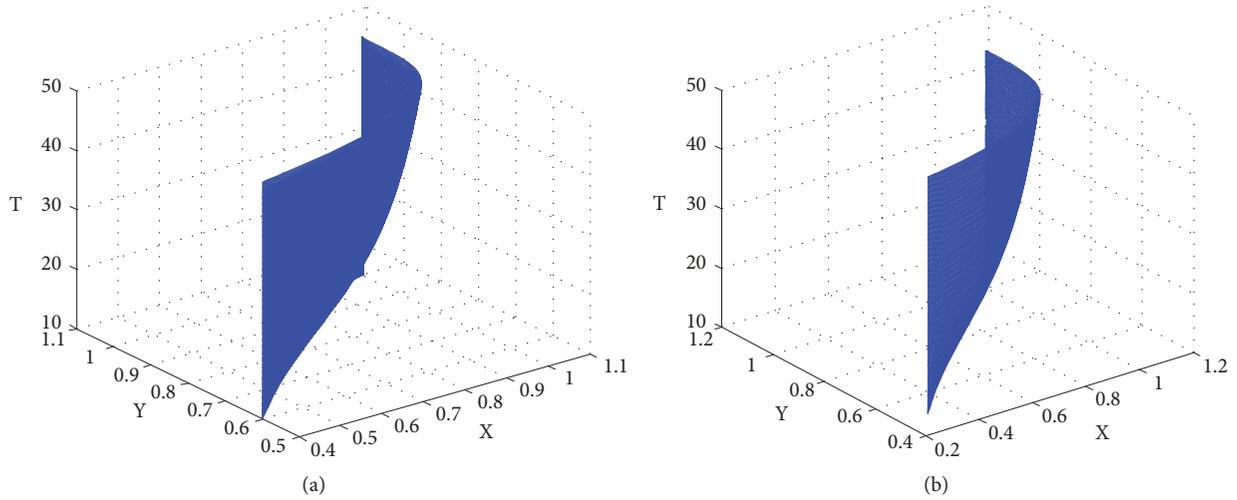


FIGURE 16: The change of  $T$  with respect to the initial values of  $(0.4,0.6)$  and  $(0.3,0.5)$  in Scenario 2.

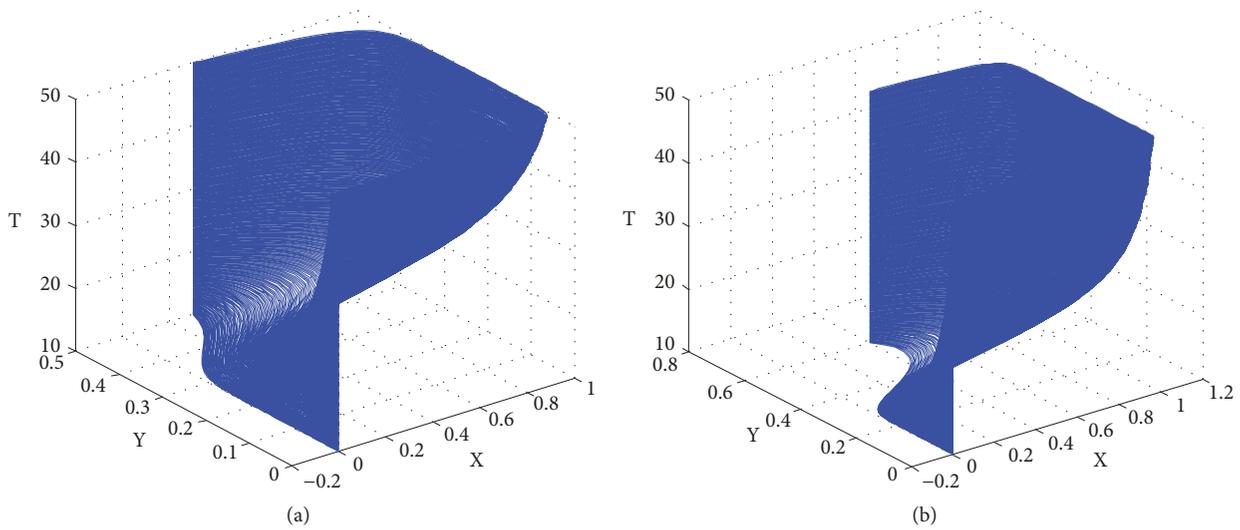


FIGURE 17: The change of  $T$  with respect to the initial values of  $(0.4,0.6)$  and  $(0.3,0.5)$  in Scenario 3.

$$\begin{aligned}
 G(x) &= x(1-x)[(1.8T+5)y-5] = 0 \\
 G(y) &= y(1-y)(22x-1) = 0
 \end{aligned}
 \tag{19}$$

The scope of  $T$  ranged from 10 to 50 Yuan. Figures 16(a) and 16(b) depicted the three-dimensional phase diagrams of replicator dynamics system, when  $(0.4,0.6)$  and  $(0.3,0.5)$  were chosen as the initial values of  $(x,y)$ , respectively. This showed the evolution process of replicator dynamics system in (19) when the passenger profit ( $T$ ) changed. Figure 16 showed that the replicator dynamics systems of  $(0.4,0.6)$  and  $(0.3,0.5)$  eventually became stable, and their equilibrium states occurred at point  $(1,1)$ . This indicated that, regardless of the initial values of  $(x,y)$ , the systems would eventually stabilize, with an ESS at the point  $(x^* = 1, y^* = 1)$ .

(3) *Scenario 3.* The replicator dynamics in Scenario 3 were

$$\begin{aligned}
 G(x) &= x(1-x)[(1.8T+22)y-22] = 0 \\
 G(y) &= y(1-y)(5x-7) = 0
 \end{aligned}
 \tag{20}$$

The scope of  $T$  was from 10 to 50 Yuan. Figures 17(a) and 17(b) illustrated the three-dimensional phase diagrams of replicator dynamics systems, when  $(0.4,0.6)$  and  $(0.3,0.5)$  were chosen as the initial values of  $(x,y)$ , respectively. These two diagrams showed the dynamic evolution process of the replicator dynamics system in (20) as the passenger's profit ( $T$ ) changed. Figure 17 indicated that the replicator dynamics systems of  $(0.4,0.6)$  and  $(0.3,0.5)$  eventually converged at the point  $(0,0)$ . This indicated that, regardless of the initial values of  $(x,y)$  and the passenger's profit ( $T$ ), the systems would eventually stabilize. Their ESSs were found at the point  $(x^* = 0, y^* = 0)$ .

### 5. Conclusions

This study used EGT to model taxi service mode choice, including the following three aspects.

First and foremost, a model formulation framework was designed to describe the setting including identifying the

strategy set and determining the payoff matrix. The game tree was described, and the game model was constructed to model the decision process.

Moreover, the replicator dynamics system was adopted to present the evolutionary process and the equilibrium state. In particular, the result of a local stability analysis provided detailed description of the decision scenario, clarifying the evolution of the system state. The dynamic evolutionary analyses, such as replicator dynamics and local stability analyses, provided interesting insights for taxi operators in making decisions about the taxi system. We specially found that, in Scenario 1, there was one ESS: D(1,1). In Scenario 2, there were two ESSs: A(0,0) and D(1,1). In Scenario 3, there was one ESS: A(0,0). From these different scenarios, it is shown that there was a stable equilibrium state, when both the passenger and taxi driver chose the dispatching mode or chose the online car-hailing mode.

Finally, we believed there were three main participant types in the taxi system: taxi company, taxi driver, and passenger. Their behavioral adjustments were introduced to discuss the impacts on the model's evolutionary process. In our case, taxi driver and passenger were the two game players and the two main participants in the taxi system. Thus, we indicated the impacts of participant behaviors on the model's evolving route, equilibrium state, and convergence speed. This was done by discussing taxi company's subsidy or penalty, taxi driver's profit ( $C$ ) and the passenger's profit ( $T$ ). More specifically, when considering the subsidy or penalty, the ESS was at point (1,1) in Scenario 1. In Scenario 2, the ESSs were at point (1,1) and point (0,0). In Scenario 3, the ESS was at point (0,0). When considering the taxi driver's profit ( $C$ ), the ESS was at point (1,1) in Scenario 1. In Scenario 2, the ESSs were at point (1,1) and point (0,0). In Scenario 3, the ESS was at point (0,0). When considering the passenger's profit ( $T$ ), ESS was at point (1,1) in Scenario 1, at point (1,1) in Scenario 2, and at point (0,0) in Scenario 3, respectively. From these results, it can be indicated that whatever influence factors changed, at least one ESS existed in different scenarios. The ESSs mainly included point (1,1) and point (0,0), existing if both passengers and taxi drivers chose the dispatching mode or the online car-hailing mode. However, these results also showed that the behaviors of taxi company, taxi driver, and the passenger impacted on our model by producing different evolutionary routes and convergence speeds in the same scenario.

Specific characteristics of main participants' behaviors in taxi system will be captured by collecting data via taxi driver and passenger surveys. They will be used to calibrate the parameters of proposed model and check the effect of model in the future. These new parameters will not affect the effectiveness of the approach, but can impact the evolutionary route, convergence speed, and the stable state of our model in this paper. In conclusion, the approach adopted in this study may be useful to understand the behaviors of main participants in taxi system and can be also transferred to other traffic systems to analyze the relationships among the participants as well as their behaviors.

## Data Availability

The values of the parameters are hypothetical by setting different evolutionary scenarios. As a result, the data from tables and figures are simulated by using Matlab software to solve the evolutionary game model.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

The Project is supported by the Fund of Liaoning Natural Science Fund Project (20180550013).

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