TRANSPORT
ISSN 1648-4142 / eISSN 1648-3480
2018 Volume 34 Issue 5: 579–590
https://doi.org/10.3846/transport.2019.11105

TRANSPORTATION NETWORK COMPANIES AND DRIVERS DILEMMA IN CHINA: AN EVOLUTIONARY GAME THEORETIC PERSPECTIVE

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Received 31 June 2018; revised 19 December 2018; accepted 1 March 2019;
first published online 13 September 2019

Abstract. The ridesourcing services market in China has recently experienced significant changes, which stem from its legalization and management policy. These changes impact multiple stakeholders of this market (e.g., drivers, passengers, government, competing services) and present them with new opportunities and challenges. This paper develops an evolutionary game model to analyse the Evolutionary Stable Strategy (ESS) between the Transportation Network Companies (TNCs) and drivers. The new model is explored and analysed with simulation experiments to observe the dynamic route of multiple stakeholders. The theoretical research and simulation results indicate that under the authorities' control over the TNCs, when the net income under strict management is higher than that of the loose management for the TNCs, the final ESS is "Legal Operation, Strict Management". When the net income under strict management is less than that of the loose management for the THCs, the strategy of "Illegal Operation, Loose Management" may gain popularity and continue to grow; in this case, the ESS may also not exist. The model indicates the strength of the government's control plays a significant role in leading the achievement of "Legal Operation, Strict Management". As a consequence, to achieve the perfect evolution of "Legal Operation, Strict Management", it is necessary for the government to impose a greater penalty on illegal drivers and ensure appropriate compensation measures. The results of the study provide a useful reference for the sustainable development of the ridesourcing services market.

Keywords: ridesourcing services, transportation network companies, new policy, evolutionary game theory, evolutionary stable strategy.

Notations

Abbreviations:

CSR – Corporate Social Responsibility;
EGT – Evolutionary Game Theory;
ESS – Evolutionary Stable Strategy;
TNCs – Transportation Network Companies.

Decision variables:

x – proportion of legal drivers;
y – proportion of strict TNCs.

Functions:

$C(x)$ – risk cost function;
f_{VD} – fitness payoffs function of the legal drivers;
f_{ID} – fitness payoffs function of the illegal drivers;
f_{SP} – fitness payoffs function of strict TNCs;
f_{LP} – fitness payoffs function of loose TNCs;
f_D – average fitness payoffs function of drivers;
f_P – average fitness payoffs function of TNCs;
$F(x)$ – replicator dynamic equations of legal drivers;
$F(y)$ – replicator dynamic equations of strict TNCs.

Index and sets:

i – index for players (drivers or TNCs), $i = 1, 2$;
j – index for different types of cost or income, $i = 1, 2, 3, 4$;
C_{ij} – the loss of player i from the j-th cost;
R_{ij} – the gain of player i from the j-th income.

Constants (parameters):

A – quadratic term ratio of function $C(x)$;
B – primary term coefficient of function $C(x)$;
C – constant term of function $C(x)$;
C_{11} – penalty cost of illegal drivers;
C_{12} – operation cost of legal drivers;
C_{21} – supervision cost of strict TNCs;

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C_{22} – maximum risk cost of strict TNCs;
C_{23} – penalty cost of loose TNCs;
C_{24} – negative externalities for TNCs;
R_{11} – basic salary of drivers;
R_{21} – reputation incentive effect of TNCs;
R_{22} – positive externalities for TNCs.

Introduction

The rapid growth of the sharing economy, represented by Airbnb, Uber, and Didi Chuxing, has broadly affected a wide variety of aspects of people's life, especially in the area of urban residents' travel using ridesourcing services. Ridesourcing refers to transportation services that connect a community of drivers with a community of passengers via mobile devices and applications (Jin *et al.* 2018). Ridesourcing services have received extensive attention from the international research community, exploring the positive and negative impacts to the community. For example, Watanabe *et al.* (2016) regard the impact of the ridesourcing services as a disruptive innovation in the taxi industry – no less than a revolution.

Nowadays, many researchers present methods and suggestions for the practical operation of ridesourcing services from the perspectives of theoretical discussion and case analysis. These studies have explored the impact of ridesharing services on: (1) urban traffic, (2) legal status, (3) taxi companies, (4) passenger safety. The results shows that the appearance of ridesourcing service makes people's travel more convenient, and enrich the travel choice. However, the issues about ridesourcing service, such as legality, competition with traditional taxi, and safety and so on, also come into being, and make the furthering development of ridesourcing service difficult in China. These studies provide valuable insights into the complex nature of the issues in the ridesharing service market. A more detailed presentation of the related work is available in Section 2.

However, most of these studies remain in the stage of qualitative description and reasoning. The exploration of mathematical models and their quantitative analyses on the problems found in the provision of ridesharing services remain largely unexplored at this time. There are many possible options available to address this gap. One option is to use EGT. Evolutionary game model is based on the bounded rationality hypothesis. It stresses the bounded rationality of game players and the dynamic process of game playing. Evolutionary game model differs from classical game theory by focusing more on the dynamics of strategy change as influenced not only by the quality of the various competing strategy, but partly by the effect of the frequency with which those various competing strategies are found in the population (Easley, Kleinberg 2010). Additional background information on EGT is available in Section 1.

EGT is widely applied to various practical problems in the field of socio-economic and management (Van Damme 1991; Tanimoto 2015), such as the evolutionary game analysis of rising urban housing and land banking issues (Zhang *et al.* 2015), the technological innovation model's selection of high-tech enterprise (Ozkan-Canbolat *et al.* 2016), green procurement game between suppliers and manufacturers (Ji *et al.* 2015), the game of coal mine safety supervision (Liu *et al.* 2015a, 2015b), the evaluation of sustainability in supply chains (Babu, Mohan 2018; Mahmoudi, Rasti-Barzoki 2018), and so on. Moreover, there have been precursors who applied EGT to traffic flow analysis (Yamauchi *et al.* 2009; Nakata *et al.* 2010; Tanimoto, Sagara 2011). Tanimoto *et al.* (2014a, 2014b), Tanimoto and Nakamura (2016) conduct the cellular automaton simulation dovetailed with EGT to explore the land changes and route-selection problem, considering social dilemma structures of traffic flows. Iwamura and Tanimoto (2018) simulate a driver's decision making-process in the complex system of traffic flow by EGT. However, there is little research on the game behaviour among the stakeholders of ridesourcing service by EGT.

In this paper, two core questions are explored and quantitatively analysed:

1) how do the autonomous game behaviours between the Transportation Network Companies (TNCs) and the drivers happen?
2) which factors will influence the equilibrium and stability of the evolutionary game?

The analytical method of the evolutionary game (Weibull 1998) is used to research the ESS between the TNCs and drivers. Further, the critical factors, which affect the equilibrium results of the evolutionary game are analysed under the supervision of the government. Finally, conclusions and suggestions are provided for the ridesourcing management.

The remainder of this paper is organized as follow. Section 1 provides background material on EGT. Section 2 presents the analysis of the related work available on ridesharing services. The evolutionary game model is presented in Section 3. The model is analysed from a theoretical perspective in Section 4; simulation studies are reported in Section 5. The conclusions are in the Last Section.

1. Background: EGT

EGT is one of the most successful mathematical framework for studying evolution in different disciplines, from Biology to Economics (Roca *et al.* 2009). As a methodology, the importance also gradually stand out in management. This theory demonstrates the relations between evolutionary stable strategies (Smith 1982) and equilibrium (Nash 1950). The theory also identifies replicator dynamics as a factor of static game based on rational choice from classical game theory (Ozkan-Canbolat *et al.* 2016). In general, EGT extends the notion of static games to settings where game participants myopically improve their decisions based on observed rewards (Coninx, Holvoet 2015).

EGT is first developed by Fisher (1930) in his attempt to describe the approximate equality of the sex ratio in mammals. Though he does not state it in special terms, it is the first way of equations that can be understood game theoretically nowadays. After him, Lewontin (1961) explicitly applies EGT to biology for the first time in his paper. Later, based on above research, Smith and Price (1973) put forward the concept of an ESS, which also makes EGT obtain huge development in various areas. Besides, the replicator equation, first introduced by Taylor and Jonker (1978), describes the evolution of the frequencies of population types taking into account their mutual influence on their fitness. This important property develops a connection between evolutionarily stable strategies with Nash equilibrium. Since then, there has been an extraordinary rise of attention by economists and social scientists in EGT.

In this work, specifically, EGT is used to model and analyse how this strategic choice of multiple stakeholders might change given different parameters such as penalty cost and compensation measures. In general, EGT provides tools and solution concepts for analysing strategic choice situations in terms of expected payoffs (Nisan *et al.* 2007).

2. Related works

In the era of the sharing economy, the rise of ridesourcing services not only creates opportunities for the TNCs and drivers, but also brings great benefits to passengers and the entire society. However, the great development and popularity of ridesourcing also presents the ridesourcing services market with new operational problems for its stakeholders. These opportunities, benefits, and operational problems have received attention in the research community. The problems involved with learning or exploring a path suitable for the development of ridesourcing services in China are worth thoughtful consideration. Botsman and Rogers (2010) introduce the pattern of collaborative consumption, taking the development of Uber in America as an example, by the online social networks. Watanabe *et al.* (2016) present a common evolutionary pattern about society, economy, and technology in the ridesourcing service market by summarizing the development trace of Uber. Tan (2016) concentrates on the Uber's practical development experience in China from the perspective of the sharing economy. Wirtz and Tang (2016) reviews the development of Uber in America and its global expansion in addition to analysing the competition between Uber and Didi Chuxing in China.

The appearance of ridesourcing services has a great influence on urban traffic (Dong *et al.* 2018; Henao, Marshall 2017). The related research has recently explored three core questions:

1) ***what are the users' differences in travel characteristics between ridesourcing and traditional taxi service?*** Rasouli and Timmermans (2014) find that the ridesourcing users are generally younger than typical travellers, and easier to travel together, and are more concerned about the travel cost. This research utilizes a survey to compare and analyse the individual experience differences between ridesourcing and traditional taxi service. Wang *et al.* (2018) use an extended technology acceptance model to understand the consumers' intention of choosing ridesourcing services, which is critical to promote operational efficiency in ridesourcing service market. Others analyse the ridesourcing effects on urban residents' travel preference, motivation and traffic regulations (Chen 2015; Rayle *et al.* 2016; Amirkiaee, Evangelopoulos 2018);
2) ***how does ridesourcing affect the traditional taxi service?*** Many scholars have presented comparative studies on ridesourcing and taxi service (Anderson 2014; Glöss *et al.* 2016; Cetin, Deakin 2019). Wang *et al.* (2016) use a partial-derivative-based sensitivity analysis to quantitatively evaluate the impacts of the TNCs' pricing strategies to the traditional taxi market performance. Harding *et al.* (2016) focus on the TNCs' impact on the taxi markets and stress concerns about driver background checks and safety. Contreras and Paz (2018) conduct a multinomial linear regression analysis, by means of a multimodal, time-series travel dataset, to estimate the effects of ride-hailing companies on taxicab ridership;
3) ***how to improve the operational efficiency in ridesourcing service market?*** Zha *et al.* (2016) propose an aggregate model where the matching between passengers and drivers are captured by an exogenous matching function. Barann *et al.* (2017) develop a one-to-one taxi ridesharing approach that matches rides with similar start and end points, and the approach is competitive, simpler to implement, and simpler to operate for the TNCs. Hughes and MacKenzie (2016) develop a spatial error regression model to investigate relationships between wait times and socioeconomic indicators throughout the Seattle, WA region, US. The results suggest that the performance of TNCs is closely correlated with the density in urban areas. Ramezani and Nourinejad (2017) present a network-scale taxi dispatch model based on the interrelated impact of normal traffic flows and taxi dynamics, to maximally matches the vacant taxis and waiting passengers. Zha *et al.* (2017) propose equilibrium models under different behavioural assumptions of labour supply in a ridesourcing services market to characterize the labour supply of ridesourcing drivers. A simple regulation scheme to reduce market power is discussed.

The legal status of ridesourcing also has sparked great debate. The issues of legalization about ridesourcing service contain the legalization of TNCs, insurance law concerned with legalization, market supervision, the impact on traditional taxi service, and related policy making, and so on. The literature indicates that ridesourcing services threaten the development of the traditional taxi market (Fritz 2014; Lobel 2016). On the other hand, research results present that ridesourcing services promote healthy competition and maintain long-term economic growth in the taxi market (Cramer, Krueger 2016; Rogers 2015). The legality of ridesourcing applications that provide only female drivers and accept only female passengers status is explored (Zhang 2016; Herbert 2016). The follow-up issues about the legalization of the ridesourcing service are also studied, such as the insurance law about ridesourcing from different angles including access system, insurance period, premium rate (Liu, Zhang 2015; Davis 2015), and so on.

Ridesourcing is very convenient for the public's travel and decreases their costs (Rogers 2015; Rayle *et al.* 2016). However, it brings about many security ricks and other problems (Rogers 2015). Consequently, the supervision in the ridesourcing services market is especially important. Hou (2015) compares and analyses the ridesourcing regulatory routine among different countries such as Singapore, the United States, the United Kingdom, and France. Some research on ridesourcing supervision have been carried out (Nie 2017; Flores, Rayle 2017). At present, the regulations on ridesourcing services consist of policy evaluation, policy making, specific regulatory policy recommendations, and the regulation thinking of traditional taxi market, and so on. Chen (2017) reports that the difficulties of ridesourcing supervision lies in the regulatory issues arising from various new formats and new models formed by the "Internet plus". The regulatory issues cannot be solved by simply applying the regulatory framework of a traditional taxi service to the ridesourcing services industry. Song and Zhang (2017) use the cost-benefit analysis method to analyze Beijing's ridesourcing rules. Authors conclude that the relevant regulatory legislation should be adjusted to cater to the ridesourcing services industry. Bengtsson (2015) validates the effectiveness of government regulation by experimenting in the taxi market. The experimental results show that effective government regulation can improve efficiency in order to achieve Pareto improvement.

With the promulgation of new policies and the emergence of industrial monopoly giants in China, the TNCs and drivers both face dilemmas. For the drivers, this is whether to indulge in illegal operation that may or may not be detected by the TNCs, while the dilemma for the TNCs is whether to take CSR to strictly manage drivers regardless of huge cost. This clearly resembles a game between two players – the TNCs and the drivers – and provides the setting for this paper in developing an EGT model to provide insights into dealing with the dilemmas involved. The strict management refers that the TNCs take CSR and strictly review drivers according to the new regulations, ensuring drivers meet the required legitimate qualifications. The loose management means that the TNCs fail to comply with the new regulation to review drivers, allowing the unstandardized drivers to continue operating. The legal operation indicates that drivers come into operation according to standards of the new regulations. The illegal operation shows that drivers fail to operate according to the requirements of the new regulations.

3. The evolutionary game model between the TNCs and the drivers

With the promulgation of new policies in China, the ridesourcing service accesses to "legal status". However, it also means that ridesourcing industry will face more administrative licensing and fewer subsidies, and the requirements for the TNCs and drivers are becoming more stringent. On the one hand, the government requested the TNCs to strictly review drivers in accordance with the new regulations. Obviously, it will increase the operational costs for the TNCs. On the other hand, due to the nature of sharing economy, the drivers would not have to face the strict access controls and pay for Taxis Company as the traditional taxi drivers. A large number of drivers are attracted to join the TNCs at a very low threshold. However, the drivers need to meet the more stringent criteria of the new policy now. Before the drivers share the fruits of the economy enough, they are pushed to the crossroads to stay or go. Thus, in order to comprehensively describe the phenomenon of cooperation or competition between TNCs and drivers, an evolutionary game model is established. The details of the evolutionary game model are presented in the following sections.

3.1. The establishment of the game model

In the context of the new policy, the TNCs and drivers are selected as game participants. Assuming that the pure strategies of TNCs are strict management and loose management, Moreover, the pure strategies of drivers are legal operation and illegal operation. To understand better the game model and facilitate the model solution, four basic assumptions are given as follows:

Assumption 1. Let x represent the proportion of drivers who take the strategy of legal operation among all drivers; the proportion of drivers who take the strategy of illegal operation is $1 - x$. Similarly, y represents the proportion of the TNCs that take the strategy of strict management among all the TNCs; the proportion of the TNCs that take the strategy of loose management is $1 - y$.

Assumption 2. When the strategy is the illegal operation for drivers, it will involve a significant penalty cost, in both administrative penalty and the detention of the vehicle, by regulators. This cost is denoted as $C_{11} > 0$. When the strategy is the legal operation for drivers, drivers need to improve the vehicle and get the relevant certificates according to the regulations. This may lead to a certain economic and time costs denoted by $C_{12} > 0$. Considering the more stringent requirements on the ridesourcing drivers, it is assumed that the necessary cost of legal operation is less than the penalty cost of illegal operation $C_{12} < C_{11}$. Otherwise, the drivers will have no motivation to choose the strategy of legal operation. This basic salary of drivers is denoted by $R_{11} > 0$.

Assumption 3. When the TNCs accept the strategy of strict management to fill CSR, energy and time cost will be paid in the process of the supervision. This cost is denoted as $C_{21} > 0$. The sharp decrease of the vehicle supply source, due to the strict management from the TNCs, make the maximum risk cost exist denoted as $C_{22} > 0$. With the continual adjustment in the course of management, the risk cost $C(x)$ is positively related to the proportion of drivers who take the strategy of illegal operation. Considering the network effects of TNCs, the demand degree of ridesourcing service is closely related to the scale of ridesourcing drivers (Pal, Scrimitore 2016; Kung, Liao 2018). It is easily understood that when the drivers of legal operation is rarely supplied, the TNCs will only develop the connection with a limited number of the passengers. It turns out that the TNCs will take on the tremendous risk cost. Assume that marginal risk cost (absolute value) increases and risk cost decreases in the situation where the portion of drivers who legally operate is increasing. Risk cost can be denoted by a quadratic function, $C(x) = A \cdot x^2 + B \cdot x + D$, through the two points, (0, C_{22}), (1, 0). Let $B = 0$ (it makes no difference to the results, then $C(x) = (1 - x^2) \cdot C_{22}$. The reputation incentive effect by the strict management is $R_{21} > 0$. When the TNCs takes the strategy of the loose management, the cost of the TNCs' not getting access to the ridesourcing service and the fine from regulators is $C_{23} > 0$.

Assumption 4. The legal operation of drivers can alleviate the congestion pressure of urban traffic and the travel problems of urban residents, which turn out to be the increase in social welfare as a whole (Ferguson 1997; Kelley 2007; Morency 2007; Caulfield 2009; Minett, Pearce 2011; Chan, Shaheen 2012). The income of the TNCs mainly refers to the positive externalities $R_{22} > 0$. In contrast, the illegal operation of drivers will have a negative influence on urban traffic and residents' travel, which turns out to be the decrease in social welfare as a whole. The loss due to negative externalities is denoted by $C_{24} > 0$.

Table 1 depicts the payoff matrix of the TNCs and drivers.

3.2. Solving a payoff matrix

When the fitness payoffs of the participants are lower than their average fitness payoffs, the participants (drivers or TNCs) adjust their strategies during the game process, so x and y are changing.

Let f_{VD} and f_{ID} be the fitness payoffs of the drivers who take different strategies (legal operation or illegal operation, respectively). According to Table 1, under the control of government regulators, f_{VD} and f_{ID} are as follows:

$$f_{VD} = y \cdot (R_{11} - C_{12}) + (1 - y) \cdot (R_{11} - C_{12}) = R_{11} - C_{12}; \tag{1}$$

$$f_{ID} = y \cdot (R_{11} - C_{11}) + (1 - y) \cdot R_{11} = R_{11} - yC_{11}. \tag{2}$$

Similarly, the fitness payoffs of the TNCs with the two different strategies (strict management or loose management, respectively) are f_{SP} and f_{LP}:

$$f_{SP} = x \cdot (R_{21} - C_{21} + R_{22}) + (1 - x) \times \left(R_{21} - C_{21} - (1 - x^2) \cdot C_{22} - C_{24}\right) = x \cdot R_{22} + R_{21} - C_{21} + (1 - x^2 - x + x^3) \cdot C_{22} - (1 - x) \cdot C_{24}; \tag{3}$$

$$f_{LP} = x \cdot (R_{22} - C_{23}) + (1 - x) \cdot (-C_{24} - C_{23}) = x \cdot R_{22} + x \cdot C_{24} - C_{24} - C_{23}. \tag{4}$$

Based on the above fitness payoff analysis, the average fitness Payoffs of the drivers f_D and of the TNCs f_P can be defined, respectively, as follows:

$$f_D = x \cdot f_{VD} + (1 - x) \cdot f_{ID} = R_{11} - x \cdot C_{12} - y \cdot C_{11} + x \cdot y \cdot C_{11}; \tag{5}$$

$$f_P = y \cdot f_{SP} + (1 - y) \cdot f_{LP} = y \cdot R_{21} - y \cdot C_{21} + y \cdot (1 - x^2 - x + x^3) \cdot C_{22} + x \cdot R_{22} - (1 - x) \cdot C_{24} - (1 - y) \cdot C_{23}. \tag{6}$$

According to the research work by Friedman (1991), Xiao and Yu (2006), in a replicator dynamic system, the growth rate of a strategy selected by the players should be equal to its fitness less the population average fitness among each player. Therefore, the replicator dynamic equations of legal operation selected by the drivers $F(x)$ and strict management selected by the TNCs $F(y)$ are as follows:

$$F(x) = x \cdot (f_{VD} - f_D) = x \cdot (1 - x) \cdot (yC_{11} - C_{12}); \tag{7}$$

$$F(y) = y \cdot (f_{SP} - f_P) = y \cdot (1 - y) \times \left((1 - x^2 - x + x^3) \cdot C_{22} - C_{21} + C_{23} + R_{21}\right). \tag{8}$$

4. The stability analysis of the evolutionary game model

According to the previous analysis, it is assumed that the necessary cost of legal operation is less than the penalty cost of illegal operation $C_{12} < C_{11}$. Consequent-

Table 1. Payoff matrix of the TNCs and drivers under the control of government regulators

	TNCs	
Drivers	Strict management	Loose management
Legal operation	$R_{11} - C_{12}$, $R_{21} - C_{21} + R_{22}$	$R_{11} - C_{12}$, $R_{22} - C_{23}$
Illegal operation	$R_{11} - C_{11}$, $R_{21} - C_{21} - (1 - x^2) \cdot C_{22} - C_{24}$	R_{11}, $-C_{24} - C_{23}$

ly, comparing the net income of the strict management $R_{21} - C_{21} - C_{22}$ with the income of loose management $-C_{23}$, this paper discusses the strategy stability of the evolutionary game between TNCs and drivers in two cases.

4.1. Case 1: net income of the strict TNCs is greater than that of the loose TNCs

When the net income of the strict TNCs is greater than that of the loose TNCs $R_{21} - C_{21} - C_{22} > -C_{23}$, then: $-C_{21} + C_{23} + R_{21} > C_{22}$, for any $x \in [0,1]$, $(1 + x^3 - x^2 - x) \in [0,1]$, so the value of $(1 + x^3 - x^2 - x) \cdot C_{22} - C_{21} + C_{23} + R_{21}$ is always more than zero. The internal equilibrium point doesn't exist (since any $x \in [0,1]$ and $y = C_{12}/C_{11}$, $F(y) > 0$). For the replicator dynamic system represented by Equations (7) and (8), the local equilibrium point of the system is (0, 0), (0, 1), (1, 0) and (1, 1). To solve the partial derivative of $F(x)$, $F(y)$ with respect to x and y respectively, the Jacobean matrix J is defined:

$$J = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}, \qquad (9)$$

where:

$$J_{11} = (1 - 2 \cdot x) \cdot (yC_{11} - C_{12});$$

$$J_{12} = x \cdot (1 - x) \cdot C_{11};$$

$$J_{21} = (3 \cdot x^2 - 2 \cdot x - 1) \cdot y \cdot (1 - y) \cdot C_{22};$$

$$J_{22} = (1 - 2 \cdot y) \times \left((1 + x^3 - x^2 - x) \cdot C_{22} - C_{21} + C_{23} + R_{21}\right).$$

The determinate "det" and the eigenvalue "eig" of J are obtained. Table 2 presents the stability analysis of the local equilibrium point of the game between the TNCs and drivers.

Table 2 shows that the local equilibrium point (1, 1) is the ESS. Under the regulations of the government, the dynamic evolutionary process of the TNCs and driver is reflected in Figure 1.

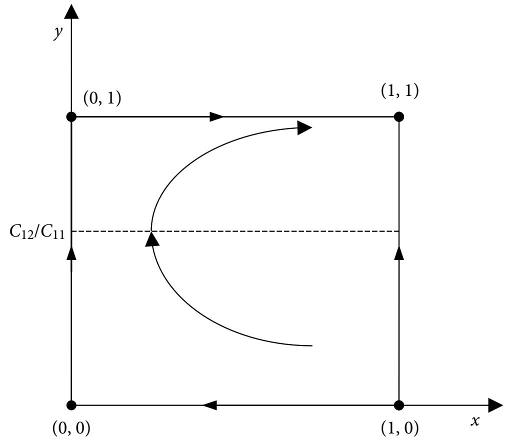

Figure 1. The dynamic diagram of the evolutionary game based on Section 4.1

From Figure 1, when the net income of the strict TNCs $R_{21} - C_{21} - C_{22}$ is greater than that of the loose TNCs $-C_{23}$, then no matter what the proportion of legal operation or illegal operation is, the TNCs will have incentives for strict management. Under this circumstance the proportion of strict TNCs will gradually increase to unity. On the other hand, the ratio of the drivers depends on the ratio of the strict TNCs. When $y < C_{12}/C_{11}$, the proportion of strict TNCs is low. The driver has a tendency towards illegal operation for lack of strict management. Thus, the ratio of legal drivers will gradually decrease. The change goes on until $y > C_{12}/C_{11}$. When the proportion of strict TNCs is high, which makes the drivers will adopt legal operation to avoid affording huge penalties due to illegal behaviour, then ratio of legal drivers will gradually increase to unity. This means that the final ESS is (1, 1).That is to say, the TNCs will eventually choose the strategy of strict management and the drivers will choose the strategy of legal operation. The perfect evolution of "Legal Operation, Strict Management" is achieved, which is expected.

4.2. Case 2: the net income of the strict TNCs is less than that of the loose TNCs

If the net income of the strict TNCs is less than that of the loose TNCs $R_{21} - C_{21} - C_{22} < -C_{23}$, then there are two scenarios to consider.

Scenario 1. When $C_{21} - R_{21} - C_{23} > C_{22}$, let $(1 + x^3 - x^2 - x) \cdot C_{22} + R_{21} - C_{21} + C_{23} = 0$, then $1 + x^3 - x^2 - x = (C_{21} - R_{21} - C_{23})/C_{22}$, but $(C_{21} - R_{21} - C_{23})/C_{22} > 1$; $1 + x^3 - x^2 - x \leq 1$, which contradicts the equation $1 + x^3 - x^2 - x = (C_{21} - R_{21} - C_{23})/C_{22}$. The internal equilibrium point doesn't exist. For the replicator dynamic system represented by Equations (7) and (8), the local equilibrium

Table 2. The stability analysis of the evolutionary game based on Section 4.1

Equilibrium point	Symbol of det J	eig J	Symbol of eig J	Stability
(0, 0)	–	$\lambda_1 = -C_{12}$; $\lambda_2 = C_{22} + R_{21} - C_{21} + C_{23}$	$\lambda_1 < 0$; $\lambda_2 > 0$	saddle point
(0, 1)	–	$\lambda_1 = C_{11} - C_{12}$; $\lambda_2 = C_{21} - C_{22} - C_{23} - R_{21}$	$\lambda_1 > 0$; $\lambda_2 < 0$	saddle point
(1, 0)	+	$\lambda_1 = C_{12}$; $\lambda_2 = C_{23} - C_{21} + R_{21}$	$\lambda_1 > 0$; $\lambda_2 > 0$	unstable point
(1, 1)	+	$\lambda_1 = C_{12} - C_{11}$; $\lambda_2 = C_{21} - C_{23} - R_{21}$	$\lambda_1 < 0$; $\lambda_2 < 0$	stable point

point of the system is (0, 0), (0, 1), (1, 0) and (1, 1). The stability of four equilibrium points is discussed according to the discrimination method of Jacobean matrix. Table 3 shows the stability analysis of the local equilibrium points of the game between the TNCs and the drivers. The local equilibrium point (0, 0) is the ESS.

The dynamic evolutionary process of the TNCs and drivers is reflected in Figure 2. When the net income of the strict TNCs $R_{21} - C_{21} - C_{22}$ is less than that of the loose TNCs $-C_{23}$, and supposing that $C_{21} - R_{21} - C_{23} > C_{22}$, the rational TNCs' best strategy is to take loose management. On the other hand, the ratio of drivers relies on the ratio of strict TNCs. When $y > C_{12}/C_{11}$, the proportion of strict TNCs is high, which turns out that the ratio of drivers who take the strategy of legal operation will gradually increase. Until $y < C_{12}/C_{11}$, the proportion of strict TNCs is low, which encourages the drivers to adopt the illegal operation due to opportunistic tendencies, and turns out that the ratio of illegal drivers will gradually increase. This means that the only ESS is (0, 0).That is to say, the TNCs will eventually choose the strategy of loose management, and the drivers will choose the strategy of illegal operation, which is similar to Prisoners' dilemma; and this situation is extremely unreasonable for ridesourcing service's healthy and sustainable development.

Scenario 2. When $0 < C_{21} - R_{21} - C_{23}) < C_{22}$, let $(1 + x^3 - x^2 - x)\cdot C_{22} + R_{21} - C_{21} + C_{23} = 0$, then$1 + x^3 - x^2 - x = (C_{21} - R_{21} - C_{23})/C_{22}$. For any $x \in [0,1]$, $1 + x^3 - x^2 - x \in [0,1]$ and $(C_{21} - R_{21} - C_{23})/C_{22} \in [0,1]$, so $\exists x_0 \in [0,1]$, subject to $(1 + x^3 - x^2 - x)\cdot C_{22} + R_{21} - C_{21} + C_{23} = 0$; $y_0 = C_{12}/C_{11}$, $y_0 \in [0,1]$. The internal equilibrium point exists, which is (x_0, y_0). For the replicator dynamic system represented by Equations (7) and (8), the local equilibrium point of the system is (0, 0), (0, 1), (1, 0) and (1, 1) and (x_0, y_0). The stability of the five equilibrium points is discussed according to the discrimination method of Jacobean matrix.

Table 4 provides the stability analysis of the local equilibrium points of the game between the TNCs and the drivers. Under this scenario, the ESS doesn't exist.

Under the regulations of the government, the dynamic evolutionary process of the TNCs and drivers is presented in Figure 3. Taking the initial position I of the system as an example to illustrate the dynamically evolutionary process in Figure 3 from I, $x < x_0$, $y > y_0$, the proportion of strict TNCs is large, which makes the income of legal drivers $R_{11} - C_{12}$ greater than that of illegal drivers $R_{11} - y \cdot C_{11}$. Thus, the proportion of legal drivers increases. Simultaneously, the income of the strict TNCs $x \cdot R_{22} + R_{21} - C_{21} + (1 - x^2 - x + x^3)\cdot C_{22} - (1 - x)\cdot R_{24}$ is greater than that of the loose TNCs $x \cdot R_{22} + x \cdot C_{24} - C_{24} - C_{23}$. The proportion of strict TNCs also increases until $x = x_0$, $y > y_0$. When $y > y_0$, the income of legal drivers is still greater than that of illegal drivers. The proportion of legal drivers continues to increase. When the system enters II, $y > y_0$, the proportion of legal drivers continues up. But $x > x_0$, the income of the

Table 3. The stability analysis of the evolutionary game based on Scenario 1 of Section 4.2

Equilibrium point	Symbol of det J	eig J	Symbol of eig J	Stability
(0, 0)	+	$\lambda_1 = -C_{12}$; $\lambda_2 = C_{22} + R_{21} - C_{21} + C_{23}$	$\lambda_1 < 0$; $\lambda_2 < 0$	stable point
(0, 1)	+	$\lambda_1 = C_{11} - C_{12}$; $\lambda_2 = C_{21} - C_{22} - C_{23} - R_{21}$	$\lambda_1 > 0$; $\lambda_2 > 0$	unstable point
(1, 0)	–	$\lambda_1 = C_{12}$; $\lambda_2 = C_{23} - C_{21} + R_{21}$	$\lambda_1 > 0$; $\lambda_2 < 0$	saddle point
(1, 1)	–	$\lambda_1 = C_{12} - C_{11}$; $\lambda_2 = C_{21} - C_{23} - R_{21}$	$\lambda_1 < 0$; $\lambda_2 > 0$	saddle point

Table 4. The stability analysis of the evolutionary game based on Scenario 2 of Section 4.2

Equilibrium point	Symbol of det J	eig J	Symbol of eig J	Stability
(0, 0)	–	$\lambda_1 = -C_{12}$; $\lambda_2 = C_{22} + R_{21} - C_{21} + C_{23}$	$\lambda_1 < 0$; $\lambda_2 > 0$	saddle point
(0, 1)	–	$\lambda_1 = C_{11} - C_{12}$; $\lambda_2 = C_{21} - C_{22} - C_{23} - R_{21}$	$\lambda_1 > 0$; $\lambda_2 < 0$	saddle point
(1, 0)	–	$\lambda_1 = C_{12}$; $\lambda_2 = C_{23} - C_{21} + R_{21}$	$\lambda_1 > 0$; $\lambda_2 < 0$	saddle point
(1, 1)	–	$\lambda_1 = C_{12} - C_{11}$; $\lambda_2 = C_{21} - C_{23} - R_{21}$	$\lambda_1 < 0$; $\lambda_2 > 0$	saddle point
(x_0, y_0)	+	σ_i; $-\sigma_i$	pure imaginary eig	central point

Note: $\sigma = \sqrt{C_{11} \cdot C_{22} \cdot x_0 \cdot y_0 \cdot (1 - x_0) \cdot (1 - y_0) \cdot (1 + 2 \cdot x_0 - 3 \cdot x_0^2)}$.

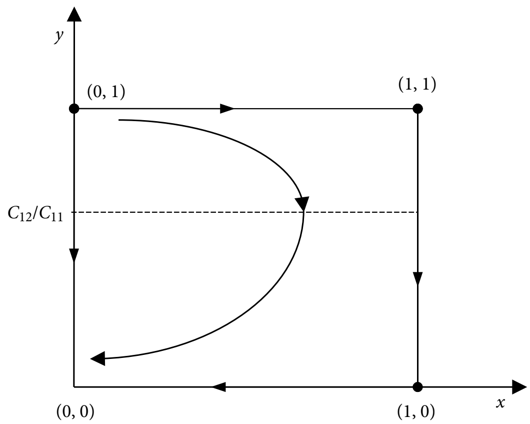

Figure 2. The dynamic diagram of the evolutionary game based on Scenario 1 of Section 4.2

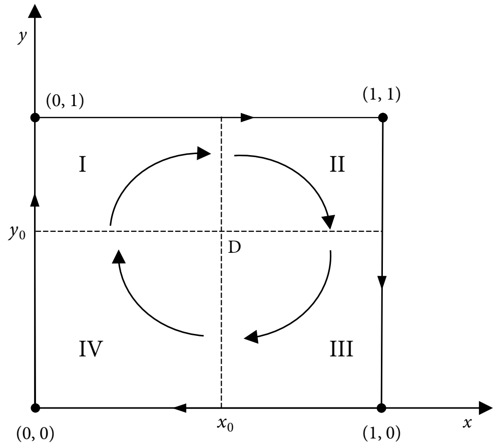

Figure 3. The dynamic diagram of the evolutionary game based on Scenario 2 of Section 4.2

strict TNCs is less than that of the loose TNCs. The proportion of strict TNCs decreases until $y = y_0$, here $x > x_0$. The proportion of strict TNCs continues down.

Beyond this, the system enters III and IV; these are symmetrical with I and II. In III, the proportion of strict TNCs and legal drivers starts down until $x = x_0$. In IV, the proportion of legal drivers is down and the proportion of strict TNCs is up. Later, the position of system returns to I. The dynamic evolutionary process repeats in such a way, eventually developing a limit cycle with the central point D through the initial value.

Scenario 3. When $C_{21} - R_{21} - C_{23} < 0$, let $(1 + x^3 - x^2 - x)\cdot C_{22} + R_{21} - C_{21} + C_{23} = 0$, then $1 + x^3 - x^2 - x = (C_{21} - R_{21} - C_{23})/C_{22}$, but $(C_{21} - R_{21} - C_{23})/C_{22} < 0$, $1 + x^3 - x^2 - x \geq 0$. The internal equilibrium point doesn't exist. For the replicator dynamic system represented by Equations (7) and (8), the local equilibrium point of the system is (0, 0), (0, 1), (1, 0) and (1, 1). The stability of four equilibrium points is discussed according to the discrimination method of Jacobean matrix. The results of stability analysis about the local equilibrium point of the game between the TNCs and the drivers are the same as that of Section 4.1, which are shown in Table 2. The local equilibrium point (1, 1) is the ESS.

The dynamic evolutionary process of the TNCs and the drivers is similar to Figure 1. The perfect evolution of "Legal Operation, Strict Management" is obtained. However, there is a significant difference in the practical cause. Although the net income of the strict TNCs is less than that of the loose TNCs initially, $C_{21} - R_{21} - C_{23} < 0$ if the risk cost falls to zero. As a limited rational homo economicus, TNCs believe that CSR has a positive impact on an organization's reputation, competitiveness and sustainability, which will increase their long-term profit (Türker 2015; Jin *et al.* 2010). Therefore, the proportion of strict TNCs will increase, and the TNCs will strictly manage illegal drivers. As with Case 1 (Section 4.1), when $y < C_{12}/C_{11}$, the proportion of strict TNCs is low, which turns out that illegal drivers will gradually increase. The change goes on until it is $y > C_{12}/C_{11}$. The proportion of strict TNCs is high, which suggests that legal drivers will gradually increase. The only ESS is (1, 1), which is expected.

5. Simulation experiments

Although the theoretical results have been analysed in Section 4, a simulation of the game model is conducted to further clarify the meaning of the model by setting different probabilities under the initial situation. The main objective of this section is to observe the dynamic route of the evolutionary game and cooperation tendency between the TNCs and the drivers. Four simulation experiments have been conducted on the simulation platform of MATLAB R2012b (*https://www.mathworks.com/products/matlab.html*). These experiments explore the behaviour of the new model while considering the reputation incentive, inadequate attention to drivers' illegal behaviour, adaptability to changing market conditions, and using different initial conditions. The results from the simulation experiments are reported below:

a) when the net income of the strict TNCs is greater than that of the loose TNCs, the initial value is set: $C_{11} = 2$, $C_{12} = 1$, $C_{21} = 4$, $C_{22} = 2$, $C_{23} = 3$, $C_{21} = 4$. Under the initial conditions for different probabilities, the dynamic route of the evolutionary game is presented in Figure 4a. The simulation results show that the ESS is (1, 1). In reality, with the implementation of new policies and the government's supervision, the reputation incentive effect plays a significant role for the development of TNCs in the ridesourcing services market. Besides, the penalties over negative management are heavy. Thus, the ratio of the TNCs choosing strict management will gradually increase to unity, which in turn promoted the rapid development of the drivers' legal operation. For the drivers, once their illegal operation is detected by strict TNCs, the penalty involved will increase the cost. At different initial probabilities, the system eventually evolves toward point (1, 1) and "Legal Operation, Strict Management" is the only ESS. This is also the expected equilibrium result;

b) when the net income of the strict TNCs is less than that of the loose TNCs, we assume that $C_{21} - R_{21} - C_{23} > C_{22}$. The initial value is set, as follows: C_{11} = 2, C_{12} = 1, C_{21} = 4, C_{22} = 2, C_{23} = 1, R_{21} = 0.5. Under the initial conditions for different probabilities, the dynamic route of the evolutionary game is presented in Figure 4b. The simulation results show that the ESS is (0, 0). Excessive management costs and insufficient punishment make the TNCs turn a blind eye to drivers' illegal behaviours, which leads to illegal behaviours prevailing. From the perspective of the ridesourcing industry, this situation is extremely unreasonable for ridesourcing healthy and sustainable development;

c) when the net income of the strict TNCs is less than that of the loose TNCs, we assume that $0 < C_{21} - R_{21} - C_{23} < C_{22}$. The initial value is set, as follows: C_{11} = 2, C_{12} = 1, C_{21} = 4, C_{22} = 2, C_{23} = 1, R_{21} = 2. Under the initial conditions for different probabilities, the dynamic route of the evolutionary game is presented in Figure 4c. The simulation results show that the ESS does not exist. Immature ridesourcing services market and new policies are unable to always keep the TNCs' strict management, in turn, which also cause the drivers' illegal behaviours. The drivers restrain their illegal behaviours when the strict TNCs are in place, while the TNCs dynamically adjust the strictness according to the ratio of legal drivers. Namely, the strategy of the TNCs and drivers is changeable with the change of market circumstances;

d) when the net income of the strict TNCs is less than that of the loose TNCs, the assumption is that $C_{21} - R_{21} - C_{23} < 0$. The initial value is set, as follows: C_{11} = 2, C_{12} = 1, C_{21} = 4, C_{22} = 2, C_{23} = 2, R_{21} = 3. Under the initial conditions for different probabilities, the dynamic route of the evolution-

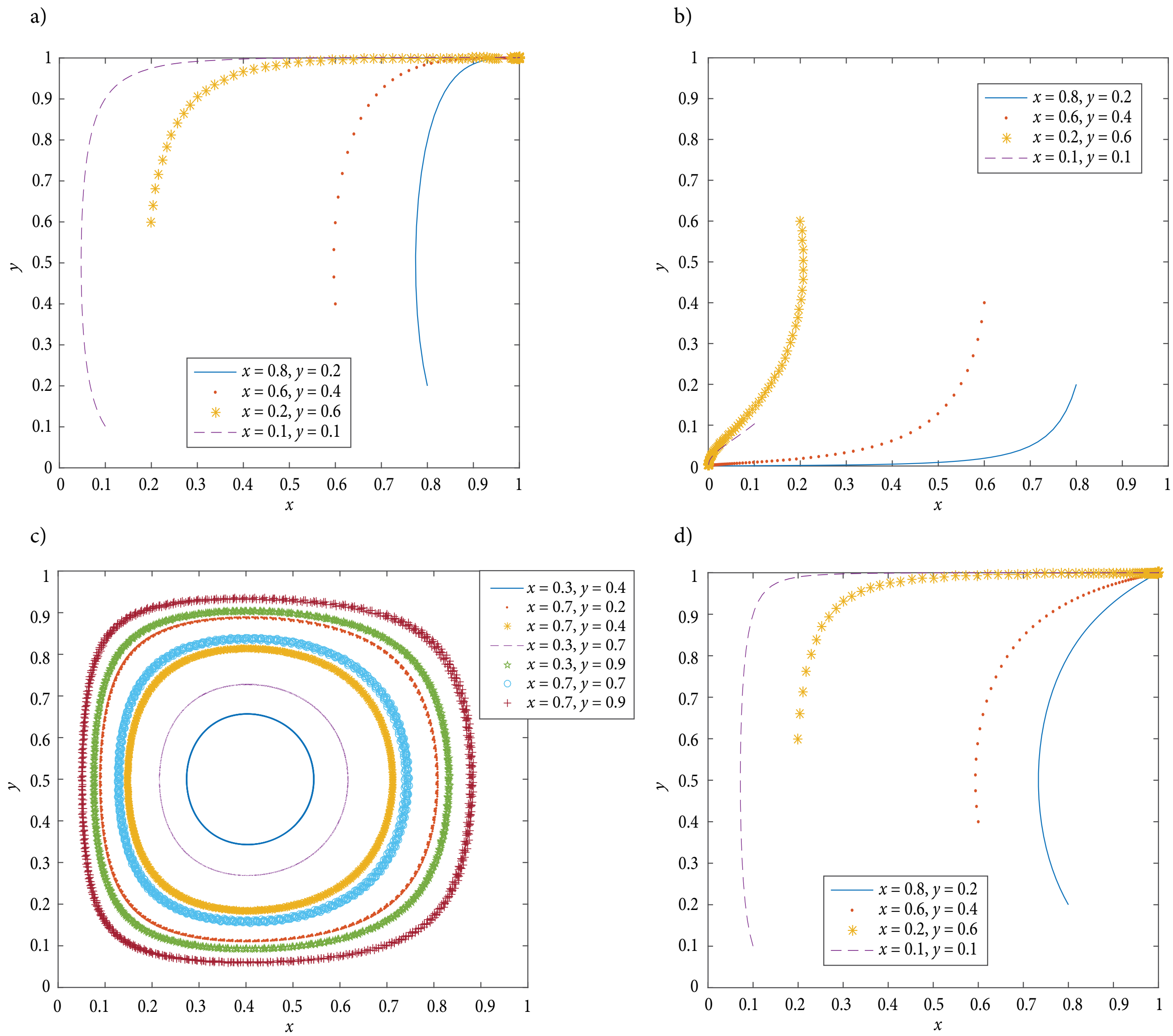

Figure 4. The evolutionary route based on Section 4.1, Scenario 1…3 of Section 4.2

ary game is presented in Figure 4d. The simulation results show that the ESS is (1, 1). The situation is similar to Section 4.1. "Legal Operation, Strict Management" is the only ESS.

Conclusions

With the accelerating pace of people's lives in China, the sharing economy has flourished unprecedentedly and plays a significant role in daily activities, especially in the aspect of urban residents' travel via ridesourcing services. The ridesourcing services industry is a typical two-sided market. The market has formed a commercial ecosystem where the TNCs act as an intermediary, connecting drivers and passengers. These stakeholders are interdependent and interact with each other. As the subject of the evolutionary game, the TNCs and the drivers have a free choice: TNCs can choose strict management or loose management; drivers can choose legal operation or illegal operation. However, for lack of the effective government regulation, the ridesourcing services market will be caught in the prisoner's dilemma, where TNCs will take the action of loose management, and drivers will take the action of illegal operation. Therefore, an effective design for regulation is needed.

In this paper, a novel evolutionary game model is proposed to evaluate the game relationship between multi-stakeholders (TNCs and drivers). More specifically, the payoff matrix between stakeholders (TNCs and drivers) under different strategies was analysed, and the replicator dynamic system was developed. Under the control of the regulatory authorities, the evolutionary game of the TNCs and the drivers will have different evolutionary stable strategies. In addition, the simulation experiments were conducted to further validate the theoretical results of the model. The research indicates that when the net income of the strict management is greater than that of the loose management for the TNCs, the final ESS is "Legal Operation, Strict Management". When the net income of the strict management is less than that of the loose management for the TNCs, the strategy of "Illegal Operation, Loose Management" may grow. The game may fall into the prisoner's dilemma, which goes against the sustainable development for the ridesourcing services industry. Additionally, the ESS may not exist. Both the TNCs and the drivers dynamically adjust the strategy to pursue the maximizing profit with the change of market environment. To achieve the perfect condition, where the TNCs accept the strategy of strict management, and drivers accept the strategy of legal operation, greater penalties on drivers with illegal operation should be imposed by the government and appropriate compensation measures should be taken for TNCs with strict management.

Aiming at the difference of net income of strict management and loose management for the TNCs, in order to make the ridesourcing industry towards sustainable development trend, the government regulators need to change the strength of compensation and punishment and improve the supervision on the ridesourcing industry, so that the TNCs are more active to rigidly manage drivers, guiding the legal operation. There are some limited aspects that should be investigated in the future work, such as the influence from other stakeholders (passengers, etc.)

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