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Analysis on the Tripartite Game of New Energy Vehicle Manufacturers Considering the Impact of Dual Credit Policy in the Context of Dual Carbon

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Abstract

Accelerating the popularization and application of new energy vehicles (NEVs) is one of the important measures for the transportation industry to achieve energy conservation and emission reduction targets. The “dual carbon goal” (carbon peaking and carbon neutrality) further clarifies the NEVs as the direction of the automobile industry and presents more requests for the transportation. Aiming at the problems of uneven development of the new energy vehicle market and imbalance of supply and demand in the integrated market, a tripartite evolutionary game model was constructed based on the evolutionary game theory. In this model, the MATLAB simulation experiments is applied to explore the interaction mechanism among the government, automobile manufacturing enterprises and consumers under the dual credit policy, and the evolutionary stable strategy (ESS) of the model was obtained in this study. The results demonstrate that under the dual credit policy (corporate average fuel consumption and new energy vehicle credits), the results of the behaviour evolution game of the government, automobile manufacturers and consumers tend to choose the strategy of “strict regulation, production of NEVs, purchase of NEVs”. At the same time, the cost of strict government regulation, the profit from reducing carbon emissions, the fact that small companies have to pay the government for producing fuel vehicles, and the profit consumers derive from taking a positive attitude are important factors affecting tripartite decision-making. The conclusions obtained in this study offer significantly references for targets for saving energy and reducing emissions and carbon neutrality in the transportation industry.

Keywords: NEVs; Carbon neutrality; Peak carbon dioxide emissions; Dual credit policy; Evolutionary game

1. Introduction

Low-carbon development is an important solution to environmental pollution and energy crisis, which has become the current consensus of global sustainable development [1]. The transportation industry is one of the most important industries in terms of energy consumption and carbon emissions, and also a key area of energy conservation and emission reduction. On the one hand, it promotes the modernization of global transport governance, the high-quality development of the service economy and inter-country connectivity cooperation. On the other hand, due to its huge energy consumption, the transportation industry meets more difficulties in decarbonization compared with other industries, and it has become the most challenging industry to achieve carbon peak, attracting the focus of scholars at home and abroad [2]. With the promotion of new energy vehicles (NEVs) and the application of green energy in the transportation industry, the characteristics of high energy consumption and high emissions in the transportation industry alleviated to a certain extent, which has a significant effect on reducing carbon emissions [3]. Accelerating the popularization and application of NEVs is one of the important measures for the transportation industry to achieve targets for saving energy and reducing emissions [4]. China produced NEVs since 2005, and made it clear that NEVs are the focus of the future development of the automobile industry. In order to improve vehicle energy efficiency and establish a long-term management mechanism for NEVs, the Chinese government promulgated the dual credit policy (corporate average fuel consumption and new energy vehicle credits) in 2017. The policy encourages automobile enterprises to produce more new energy models and promote the healthy development of NEVs by restricting automobile enterprises with negative credits from producing models with substandard fuel consumption [5] and adopting other punishments. After the implementation of the policy, China’s vehicles saved 27.43 million tons of fuel and reduced about 86.95 million tons of carbon dioxide emissions over the past five years, making an important contribution to the carbon emission reduction of the automobile industry. However, unfortunately, some enterprises are still not willing to produce NEVs, which results in NEVs credits being zero or even below. For example, according to the 2019 average fuel consumption scores of automobile enterprises published by the Ministry of Industry and Information Technology of China, nearly 40 percent of Chinese automobile manufacturers have negative average fuel consumption credits, while of 27 imported automobile enterprises, only four, including Tesla and Porsche, have positive fuel consumption credits, while the remaining 23 are negative. In terms of new energy vehicle enterprises, 69 enterprises obtained positive credits, 17 automobile enterprises obtained zero, and 27 enterprises obtained negative [6]. Moreover, due to the low price of credits, negative corporate average fuel consumption (CAFC) credits and negative NEV credits could be offset by positive NEV credits, which greatly reduces the willingness of enterprises to independently research, develop and produce

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NEVs, and is not conducive to the low-carbon development of the automobile industry. In order to solve the problems such as low production willingness of the new energy vehicle manufacturers and unbalanced supply and demand of the points market, evolutionary game theory in this study aims to explore the interaction mechanism of the government, automobile manufacturers and consumers under the dual credit policy, so that the dual credit policy could release more carbon emission reduction potential and further promote the energy saving, emission reduction and low carbon development of Chinese automobile industry and better achieve the dual carbon goal.

Focusing on the manufacturing problems of NEVs, scholars explored their shortcomings from the perspective of cost control, and proposed countermeasures to strengthen the cost control of automobile manufacturers, thus seeking ways and methods to reduce cost and increase efficiency of new energy automobile enterprises [7]. The influence of the cost of sales threshold and service level on the income of automobile manufacturers was analyzed by Peng and Lin [8]. After the implementation of the dual credit policy, the electrification and hybrid process of traditional automobile enterprises continued to accelerate. Since a proper credit transaction price could reduce the impact of the dual credit policy on automobile enterprises, scholars suggested that automobile manufacturers and automobile enterprises cooperate with existing suppliers to jointly address the challenges of dual credit [9]. The optimal decision of automobile manufacturers could also be made from the perspective of both supply and demand drivers [10]. With the introduction of the dual-carbon goal, the development of a green, low-carbon and circular economy requires enterprises to adjust the scale of the new energy automobile industry and consider how automobile manufacturers could achieve low-carbon production under government supervision [11]. The study concluded that large new energy vehicle manufacturers need to make NEVs greener to avoid customer loss and cost increase [12]. It became an industry consensus that the dual-carbon strategy leads to the sustainable and high-quality development of NEVs. However, few relevant studies took dual carbon policy into account. In addition, in the implementation of the dual credit policy, the policy choices of the government, automobile manufacturers and consumers interact with each other, so it is not comprehensive enough to consider only one or two topics. Therefore, based on the dual carbon background, from the perspective of bounded rationality, the evolutionary game method is used to analyze and predict the group behavior of multiple stakeholders of the dual credit policy in this study, which is of great significance for the further development of the new energy vehicle industry.

The importance and originality of this study is mainly reflected in the following two factors. On the one hand, since the dual credit policy is constantly revised and the impact of subsequent policy changes, the problem is described from a dynamic perceptive and the dynamic change process is shown in this study. On the other hand, carbon emission reduction subsidies are introduced into the tripartite evolutionary game model to explore the influence of “peak carbon dioxide emissions” and “carbon neutrality” more comprehensively on the decision-making of the tripartite subjects, and MATLAB is adopted for simulation analysis and verification, making the results of the evolutionary game more optimized and accurate.

The rest of this study is structured as follows. The second section contains a literature review, combing and analyzing the relevant literature. The third and fourth sections are about the construction and equilibrium analysis of the game model of government, automobile manufacturers and consumers. Reasonable assumptions are made about the model, and the evolutionary game revenue matrix and replication dynamic function are constructed among the three parties. Then the evolutionary equilibrium point is derived and the stability analysis is carried out. The fifth section is the situation and simulation analysis of the evolution results. Each stability situation is simulated by MATLAB, and the above model is further analyzed. The sixth section is the strategic enlightenment, summarizing the main research results of this study and puts forward relevant suggestions combined with the current situation of the new energy vehicle industry.

2. State of the art

Before the implementation of the dual credit policy, in order to control the energy consumption caused by the excessive growth of automobiles, the Chinese government issued the Fuel consumption limits for passenger Cars [13]. Among them, the specific effect of energy conservation and environmental protection of NEVs mainly depends on the number of NEVs and China’s power generation structure, so the effect is highly uncertain [14]. Compared with NEVs, traditional fuel vehicles account for a larger proportion of vehicle fuel consumption. Therefore, attention should be paid to the energy saving and consumption reduction of traditional fuel vehicles while developing the NEVs [15]. In 2017, China implemented the dual credit policy. Under the constraints of the dual credit policy, new energy vehicle manufacturers focus on the production of NEVs and make profits by selling positive points [16]. In general, the dual credit policy is conducive to the production of NEVs. However, when vehicle manufacturers’ NEVs credits by the end of the year are not up to the standard, the dual credit policy would be detrimental to the production of energy-efficient vehicles [17]. In order to encourage enterprises to reduce pollution and emissions, the Chinese government introduced the dual credit policy. Given that the transportation industry is one of the three key areas of energy conservation and emission reduction in China, speeding up the green and low-carbon transformation of the transportation industry has become an important measure to achieve carbon peak and carbon neutrality [18]. Under the requirements of the dual-carbon goal, the production and sales volume of NEVs increase significantly, domestic new energy brands develop rapidly, and the upstream and downstream industrial chain of the industry keep a sound momentum [13]. Some studies estimate that after 2030, pure electric models will become the mainstream car models in China [19]. According to studies by scholars such as Su et al., the sales volume of NEVs in China is not high at present, and the environmental protection effect is not obvious. In addition, domestic battery technology for NEVs has not made a breakthrough, and there are still problems such as incomplete infrastructure including charging piles, insufficient power supply and limited driving range [21]. Existing studies took into account the production conditions of new energy vehicle manufacturers under the constraints of dual credit policy without considering the impact of dual carbon policy and dual credit policy on the production behavior of NEVs, which could not reflect the situation of the current new energy vehicle industry. On the basis of considering dual carbon the existing dual credit policy, the tripartite game is used to study the strategy selection of all parties under the dual credit policy and relevant suggestions are put forward in this study so as to help promote new energy vehicle industry's goal of dual carbon.

China implemented a series of policies to develop NEVs, such as the dual credit policy and the subsidy policy. It has been confirmed that reducing subsidies for NEVs is feasible and attention should be paid to the synergistic effect of various policy tools in policy making by Ye et al. [22] through empirical analysis from the perspective of dual credit policy. Studies show that subsidies enhance the promotion of NEVs and reduce air pollutant emissions, and PSM-DID method and tool strategy are employed to verify the validity of the empirical results [23]. Based on the panel vector autoregressive model, the dynamic change characteristics of the influence of the dual credit policy on the dual performance of the operation and environment of new energy vehicle enterprises are analyzed by Li and Xiong [24], and then a comparative test was carried out by using the counterfactual analysis method. In addition, a policy dependency mapping method was proposed, 175 policies on NEVs from 2006 to 2016 were analyzed, and adoption targets from 2016 to 2020 were predicted by Zhang et al. [25]. Based on genetic algorithms, scholars made the electrification decision of traditional automobile manufacturers under the dual credit policy, and apply dynamic programming to investigate the price changes of traditional automobile manufacturers under the dual credit policy and the optimal timing of electrification [26]. Some studies applied differential models to analyze the changes in the scale, intensity and structure of R&D (research and development) input of new energy vehicle enterprises from the planning stage to the implementation stage of the dual credit policy, and used dynamic optimal control theory to study and analyze the cost of production inventory and optimal production decision under the background of the dual credit policy and carbon trading [24]. An R&D decision-making model was proposed by Meng et al. [27], considering the capital constraints of suppliers, to obtain the optimal strategy to solve these constraints and promote the development of NEVs. Through the tripartite game, some studies found that the output of NEVs, is positively correlated with the proportion of NEV credits required and negatively correlated with the average fuel consumption target value of the enterprise since the implementation of the dual credit policy. Therefore, increasing the NEV credit ratio requirement or reducing the average fuel consumption target value of enterprises is an effective measure to promote the development of the new energy vehicle industry [28]. A two-party game model, exploring the mechanism of the influence of policy changes on the evolution of R&D strategy in NEV cooperative innovation network, was constructed by Han et al. [29].

From the perspective of subsidy policies, the formation mechanism and dynamics of integral price and the optimal production decision of manufacturers were studied by He et al. [26] by establishing a game model of capacity utilization of three types of manufacturers. A typical production model of customer vendor (CV) supply chain and NEV supply chain system that used a mix of subsidy policy and dual credit policy were established by Li et al through linear programming [30], giving birth to the solution for NEV and CV production decisions and dual credit transactions. A tripartite game model was established, arguing that the combination of R&D subsidy policy with reverse spillover rate change and dual credit policy could promote enterprise technological innovation by Yu et al. [31]. Studies proved that in different situations, enterprises would always choose to produce NEVs, and the final choice of the government was determined by the frequency of inspection in the subsidy process, and finally put forward relevant suggestions for the stable promotion of NEVs and how to alleviate the relevant financial pressure faced by the government [32]. In addition, some scholars constructed a game model between consumers and the government, analyzing the interaction mechanism between consumers' strategic choice of purchasing NEVs and the government's financial subsidy incentive strategy choice, and gave corresponding policy suggestions [33]. An evolutionary game model to simulate the interrelation among the government, automobile manufacturers and consumers was established, and the decision to recycle waste batteries under government subsidies was made by Zhang et al. [25]. In addition, some studies conducted an interest coordination analysis on stakeholders of Chinese new subsidy policy for hydrogen fuel cell vehicles from the perspective of evolutionary game theory [34]. Therefore, from the subsidy stage to the subsidy decline stage, scholars at home and abroad systematically sorted out a large number of game relationships among relevant topics of new energy vehicle policies. Through these studies, we could clearly see the positive role of new energy vehicle policies in promoting the development of new energy automobile industry. In the multi-stage game, the strategy selection of the participants is sequential, and the three players involved in this study make decisions at the same time. And when evolutionary games are used for analysis, most of them are two-sided games, and there is little literature on the discussion of three parties of new energy vehicle manufacturers.

In view of this, this study, considering dual carbon policy and dual credit policy is going to conduct the game payment matrix of the tripartite game among the government, automobile manufacturers and consumers analyze. Besides, the group behavior of participants in the new energy automobile industry through MATLAB numerical simulation will also be analyzed and predicted. Therefore, suggestions are put forward for the low-carbon emission reduction and high-quality sustainable development of the new energy automobile industry.

3. Model construction

For the purposes of game analysis, without changing the essence of the problem, the following assumptions are made in this study.

(1) The three parties of the game include the government, automobile manufacturers and consumers, all of which are bounded rationality.

(2) Behavioral strategies. There are two strategic options for the government: strict regulation and loose regulation. There are two strategic choices for automobile manufacturers: to produce NEVs, or not. There are two strategic choices for consumers: NEVs and traditional fuel vehicles.

(3) The selection ratio of gaming strategies.

In the game among the government, automobile manufacturers and consumers, assuming that the probability of strict government regulation is $x\left(0 \le x \le 1\right)$, and the probability of loose regulation is $\left(1-x\right)$. The probability of an automobile manufacturer producing NEVs is $y\left(0 \le y \le 1\right)$, and the probability of not producing NEVs is $\left(1-y\right)$. The probability of consumers buying NEVs is $z\left(0 \le z \le 1\right)$, and the probability of consumers buying traditional fuel vehicles is $\left(1-z\right)$.

(4) Parameter assumptions

Hypothesis 1: If the automobile manufacturer chooses to produce NEVs, the R&D cost to be paid is $C_1 + \Delta C$, and the revenue obtained by the manufacturer is R_1, which is the revenue from the sale of the NEVs. And the cost of purchasing new energy vehicle credits is N_1, and the cost of deducting the average fuel credits is F_1. If the enterprise's new energy vehicle credits meet the standard, the excess credits could be sold or offset against the average negative fuel consumption credits, the revenue obtained at this time is $W_1 + \Delta W_1$, W_1 is the income obtained from selling to the enterprise whose new energy score is not up to standard, and ΔW_1 is the income obtained from selling to the enterprise whose average fuel score is not up to the standard. As far as the government is concerned, if strict regulatory policies are implemented, the cost paid by the government is A_1 and the profit obtained is ΔA_1 (this study mainly refers to the contribution of the "double carbon" target), and the loss of the automobile manufacturing enterprise is Q_1. The government carbon subsidy for consumers buying NEVs is S. As enterprises actively respond to the national policy call to produce NEVs, consumers who purchase NEVs get additional benefit U_1, including not only the improvement of the cost performance of NEVs, but also the potential benefits such as environmental optimization. When consumers buy traditional fuel vehicles, the enterprise income is R_3.

Hypothesis 2: If the automobile manufacturer chooses to produce traditional fuel vehicles, the R&D cost to be paid is C_1, the sales volume brought to the manufacturer is R_2, the cost of purchasing new energy vehicle credits is N_2, and the cost used to offset the negative fuel credits is F_2. In this case, the cost of strict regulation by the government is A_2, the income obtained is ΔA_2, and the loss of the automobile manufacturing enterprise is Q_2. At the same time, in order to achieve the "double carbon" target as soon as possible, the government encourages enterprises to produce NEVs and imposes fines on traditional fuel vehicle enterprises K_1. If the carbon emissions exceed the standard, the government would need to pay R for the treatment of air pollution. In this case, the benefit obtained from consumers choosing traditional fuel vehicles is U_2 (obviously $U_1 > U_2$), and the tax to be paid to the government is K_2.

In addition, the probability that the NEV credits fails to reach the standard value is set as α, the probability that the actual output of fuel vehicles is higher than the target output is set as β, and the enterprise income is set as W_2 if the actual output of fuel vehicle is lower than the target output. The payoff matrix of evolutionary game is shown in Table 1.

Table 1. Evolutionary game payoff matrix of the government, automobile manufacturers and consumers

Government	Enterprise	Consumers	
		Buy NEVs z	**Buy traditional fuel vehicles** $1-z$
Strict x	Production y	$-A_1 - S + \Delta A_1$, $-(C_1 + \Delta C) + R_1 - \alpha N_1 + (1-\alpha)$ $(W_1 + \Delta W_1) - \beta F_1 - Q_1 + (1-\beta)W_2$, $U_1 + S$	$-A_1 + K_2 + \Delta A_1 - R$, $-(C_1 + \Delta C) + R_3 - \alpha N_1 + (1-\alpha)$ $(W_1 + \Delta W_1) - \beta F_1 - Q_1 + (1-\beta)W_2$, $-K_2$
	Not production $1-y$	$-A_2 - S + K_1 + \Delta A_2$, $-C_1 + R_2 - N_2 - \beta F_2$ $-K_1 - Q_2 + (1-\beta)W_2$, S	$-A_2 + K_2 + \Delta A_2 + K_1 - R$, $-C_1 + R_3 - N_2 - \beta F_2$ $-K_1 - Q_2 + (1-\beta)W_2$, $U_2 - K_2$
Not strict $1-x$	Production y	$-S$, $-(C_1 + \Delta C) + R_1 - \alpha N_1 - \beta F_1$ $+(1-\alpha)(W_1 + \Delta W_1) + (1-\beta)W_2$, $U_1 + S$	$-R$, $-(C_1 + \Delta C) + R_3 - \alpha N_1 - \beta F_1 +$ $(1-\beta)W_2 + (1-\alpha)(W_1 + \Delta W_1)$, 0
	Not production $1-y$	$K_1 - S$, $-C_1 + R_2 - N_2 - \beta F_2 - K_1 + (1-\beta)W_2$, S	$K_1 - R$, $-C_1 + R_3 - N_2 - \beta F_2 - K_1 + (1-\beta)W_2$, U_2

4. Model analysis

4.1 Replication dynamic equation of tripartite game

Suppose U_{1x} and U_{1n} are the expected returns when the government chooses the strict regulation strategy and loose one respectively, and $\overline{U_x}$ is the average expected return of the government. The following equation (1) could be obtained.

$$\overline{U_X} = xU_{1x} + (1-x)U_{1n} \quad (1)$$

The replication dynamic equation of the government population is as follows, see equation (2).

$$F(x) = \frac{dx}{dt} = x*\left(U_{1x} - \overline{U_X}\right) \quad (2)$$

Suppose U_{2y} and U_{2n} are the expected returns of the automobile manufacturers when they choose to produce NEVs and not to respectively, and $\overline{U_y}$ is the average expected income. The following equation (3) could be obtained.

$$\overline{U_y} = yU_{2y} + (1-x)U_{2n} \quad (3)$$

The replication dynamic equation of enterprise population is as follows, see equation (4).

$$F(y) = \frac{dy}{dt} = x*\left(U_{2y} - \overline{U_y}\right) \quad (4)$$

Suppose U_{3z} and U_{3n} are the expected earnings when consumers choose to buy NEVs and traditional fuel vehicles respectively, and $\overline{U_z}$ is the average expected earnings of consumers. The following could be obtained through the above analysis, see equation (5)

$$\overline{U_z} = zU_{3z} + (1-z)U_{3n} \quad (5)$$

The replication dynamic equation of the consumer population is shown below (6).

$$F(z) = \frac{dz}{dt} = z*\left(U_{3z} - \overline{U_z}\right) \quad (6)$$

By sorting out equations (2), (4) and (6), the replication dynamic equations of the three could be obtained. The 3D dynamical system of $F(x)$, $F(y)$, $F(z)$ is shown in the following equation (7).

$$\begin{cases} F(x) = x(1-x)\begin{bmatrix} (-A_1 + A_2 + \Delta A_1 - \Delta A_2)y \\ -K_2 z + \Delta A_2 + K_2 - A_2 \end{bmatrix} \\ F(y) = y(1-y)\begin{bmatrix} (Q_2 - Q_1)x + (R_1 - R_2)z \\ -\Delta C - \alpha N_1 + N_2 \\ +(1-\alpha)(W_1 + \Delta W_1) \\ -\beta(F_1 - F_2) + K_1 \end{bmatrix} \\ F(z) = z(1-z)\left[K_2 x + (U_1 + U_2)y + S - U_2\right] \end{cases} \quad (7)$$

4.2 Evolutionary equilibrium point

According to equation (7) of the 3D dynamical system, the evolutionary game among government, automobile manufacturers and consumers is studied.

Make $P_1 = -A_1 + A_2 + \Delta A_1 - \Delta A_2$, $P_2 = -K_2$, $P_3 = \Delta A_2 + K_2 - A_2$, $P_4 = Q_2 - Q_1$, $P_5 = R_1 - R_2$, $P_6 = -\Delta C - \alpha N_1 + N_2 + (1-\alpha)(W_1 + \Delta W_1) - \beta(F_1 - F_2) + K_1$, $P_7 = U_1 + U_2$, $P_8 = S - U_2$.

The equation (7) could be simplified to equation (8) of the 3D dynamical system.

$$\begin{cases} F(x) = x(1-x)(P_1 y + P_2 z + P_3) \\ F(y) = y(1-y)(P_4 x + P_5 z + P_6) \\ F(z) = z(1-z)(K_2 x + P_7 y + P_8) \end{cases} \quad (8)$$

Proposition 1: The equilibrium points of eight groups adopting pure strategy in equation (8) of the 3D dynamical system are $E_1 = (0,0,0)$, $E_2 = (1,0,0)$, $E_3 = (0,1,0)$, $E_4 = (0,0,1)$, $E_5 = (1,1,0)$, $E_6 = (1,0,1)$, $E_7 = (0,1,1)$ and $E_8 = (1,1,1)$ respectively

Proof: Suppose $F(x) = \frac{dx}{dt} = 0$, $F(y) = \frac{dy}{dt} = 0$, $F(z) = \frac{dz}{dt} = 0$, get $E_1 = (0,0,0)$, $E_2 = (1,0,0)$, $E_3 = (0,1,0)$, $E_4 = (0,0,1)$, $E_5 = (1,1,0)$, $E_6 = (1,0,1)$, $E_7 = (0,1,1)$ and $E_8 = (1,1,1)$ as the eight equilibrium points of the 3D dynamical system (8).

When $F(x) = \frac{dx}{dt} = 0$, $F(y) = \frac{dy}{dt} = 0$, $F(z) = \frac{dz}{dt} = 0$, and x, y, z are not equal to 0 or 1, Proposition 2 is obtained.

Proposition 2: The six possible single-population adopting pure strategy equilibrium points in this system are $E_9\left(-\frac{P_7 + P_8}{K}, 1, -\frac{P_1 + P_3}{P_2}\right)$, $E_{10}\left(1, -\frac{K + P_8}{P_7}, -\frac{P_4 + P_6}{P_5}\right)$, $E_{11}\left(-\frac{P_2 + P_3}{P_1}, -\frac{P_3}{P_1}, 1\right)$, $E_{12}\left(-\frac{P_8}{K}, 0, -\frac{P_3}{P_2}\right)$, $E_{13}\left(-\frac{P_6}{P_4}, -\frac{P_3}{P_1}, 0\right)$, $E_{14}\left(0, -\frac{P_8}{P_7}, -\frac{P_6}{P_5}\right)$

Proof: when $x = 1, 0 < y < 1, 0 < z < 1$, if $F_X = F_Y = 0$ is constant, then $E_{10}\left(1, -\frac{K + P_8}{P_7}, -\frac{P_4 + P_6}{P_5}\right)$ is the equilibrium point of the 3D dynamic system. Similarly, it could be proved that the other five points are also the equilibrium points of the 3D dynamical system.

Proposition 3: The 3D dynamical system may have a mixed strategy equilibrium point $E_{15}(x^*, y^*, z^*)$, and $x^*, y^*, z^* \in (0,1)$.

Proof: For this system, when condition $x^*, y^*, z^* \in (0,1)$ is satisfied, equation $F(x) = \frac{dx}{dt} = 0$, $F(y) = \frac{dy}{dt} = 0$, $F(z) = \frac{dz}{dt} = 0$ is also established, and equation (9) of 3D dynamic system is obtained, solving equation set (9), (x^*, y^*, z^*) will be the possible equilibrium point of this system, see equation (10)

$$\begin{cases} G\left(x^*, y^*, z^*\right) = x(1-x)\left(P_1 y + P_2 z + P_3\right) \\ M\left(x^*, y^*, z^*\right) = y(1-y)\left(P_4 x + P_5 z + P_6\right) \\ K\left(x^*, y^*, z^*\right) = z(1-z)\left(K_2 x + P_7 y + P_8\right) \end{cases} \tag{9}$$

Solution:

$$\begin{cases} x^* = -\dfrac{P_1P_5P_8 + P_2P_6P_7 - P_3P_5P_7}{KP_1P_5 + P_2P_4P_7} \\ y^* = -\dfrac{KP_3P_5 - KP_2P_6 + P_2P_4P_8}{KP_1P_5 + P_2P_4P_7} \\ z^* = -\dfrac{KP_1P_6 - P_1P_4P_8 + P_3P_4P_7}{KP_1P_5 + P_2P_4P_7} \end{cases} \tag{10}$$

4.3 Stability analysis of equilibrium point

The equilibrium point obtained by copying the dynamic equation is not necessarily the evolutionary stable strategy of the system. Therefore, according to Lyapunov's stability theory, the asymptotic stability of the system at the equilibrium point could be judged by analyzing the eigenvalues of Jacobi matrix. That is, the necessary and sufficient condition for the stability of the system is that all eigenvalues of the Jacobian matrix have negative real parts.

The evolutionary game process of the government, manufacturers and consumers is studied according to the 3D dynamic system, and J is set as the Jacobian matrix, see equation (11).

$$J = \begin{bmatrix} (1-2x)\left(P_3 + P_1 y + P_2 z\right) & x(1-x)P_1 & x(1-x)P_2 \\ y(1-y)P_4 & (1-2y)\left(P_6 + P_4 x + P_5 z\right) & y(1-y)P_5 \\ K_2 z(1-z) & -P_7 z(1-z) & (1-2z)\left(K_2 x + P_7 y + P_8\right) \end{bmatrix} \tag{11}$$

The Jacobian matrix eigenvalues corresponding to 15 equilibrium points of the 3D dynamic system are calculated to judge the asymptotic stability of the equilibrium points. The Jacobian matrix eigenvalues corresponding to the 15 stable points are shown in Table 2.

Table 2. Equilibrium point of the system and its eigenvalues

Equilibrium	λ_1	λ_2	λ_3	Asymptotic stability
$E_1(0,0,0)$	$\Delta A_2 + K_2 - A_2$	$-\Delta C - \alpha N_1 + N_2 + (W_1 + \Delta W_1) - \beta(F_1 - F_2) + K_1$	$S - U_2$	conditions①
$E_2(1,0,0)$	$-\Delta A_2 - K_2 + A_2$	$Q_2 - Q_1 - \Delta C - \alpha N_1 + N_2 + (1-\alpha)$ $(W_1 + \Delta W_1) - \beta(F_1 - F_2) + K_1$	$K_2 + S - U_2$	conditions②
$E_3(0,1,0)$	$-A_1 + \Delta A_1 + K_2$	$\Delta C + \alpha N_1 - N_2 - (1-\alpha)(W_1 + \Delta W_1)$ $+\beta(F_1 - F_2) - K_1$	$U_1 + S$	unstable
$E_4(0,0,1)$	$\Delta A_2 - A_2$	$(1-\alpha)(W + \Delta W_1) - (F_1 - F_2)\beta$ $+R_1 - R_2 - \Delta C - \alpha N_1 + N_2 + K_1$	$-S + U_2$	conditions③
$E_5(1,1,0)$	$A_1 - \Delta A_1 - K_2$	$Q_1 - Q_2 - (1-\alpha)(W_1 + \Delta W_1)$ $+(F_1 - F_2)\beta + \Delta C + \alpha N_1 - N_2 - K_1$	$K_2 + U_1 + S$	unstable
$E_6(1,0,1)$	$-\Delta A_2 + A_2$	$-Q_1 + Q_2 + (1-\alpha)(W + \Delta W_1) - (F_1 - F_2)\beta$ $+R_1 - R_2 - \Delta C - \alpha N_1 + N_2 + K_1$	$-K_2 - S + U_2$	conditions④
$E_7(0,1,1)$	$-A_1 + \Delta A_1$	$-(1-\alpha)(W + \Delta W_1) + (F_1 - F_2)\beta$ $-R_1 + R_2 + \Delta C + \alpha N_1 - N_2 - K_1$	$-U_1 - S$	conditions⑤
$E_8(1,1,1)$	$A_1 - \Delta A_1$	$Q_1 - Q_2 - (1-\alpha)(W + \Delta W_1) + (F_1 - F_2)\beta$ $-R_1 + R_2 + \Delta C + \alpha N_1 - N_2 - K_1$	$-K_2 - U_1 - S$	conditions⑥

Taking $E_1(0,0,0)$ as an example, the conditions satisfying the evolutionary stable strategy are discussed. The eigenvalues of the Jacobian matrix of the system at equilibrium point $E_1(0,0,0)$ are $\lambda_1 = \Delta A_2 + K_2 - A_2$, $\lambda_2 = -\Delta C - \alpha N_1 + N_2 + (1-\alpha)(W_1 + \Delta W_1) - \beta(F_1 - F_2) + K_1$, $\lambda_3 = S - U_2$. If λ_1, λ_2, λ_3 meet condition①.

$$\begin{cases} \Delta A_2 + K_2 - A_2 < 0 \\ \begin{bmatrix} -\Delta C - \alpha N_1 + N_2 + (1-\alpha)(W_1 + \Delta W_1) \\ -\beta(F_1 - F_2) + K_1 \end{bmatrix} < 0 \\ S - U_2 < 0 \end{cases} \quad ①$$

This equilibrium point is also the asymptotic stability condition which the other four equilibrium points on, as shown in Table 3.

Table 3. Equilibrium stability conditions of 3D dynamic system

Equilibrium	Condition of stability	number
$E_1(0,0,0)$	$\Delta A_2 + K_2 - A_2 < 0$ $-\Delta C - \alpha N_1 + N_2 + (1-\alpha)(W_1 + \Delta W_1) - \beta(F_1 - F_2) + K_1 < 0$ $S - U_2 < 0$	①
$E_2(1,0,0)$	$-\Delta A_2 - K_2 + A_2 < 0$ $Q_2 - Q_1 - \Delta C - \alpha N_1 + N_2 + (1-\alpha)(W_1 + \Delta W_1) - \beta(F_1 - F_2) + K_1 < 0$ $K_2 + S - U_2 < 0$	②
$E_4(0,0,1)$	$\Delta A_2 - A_2 < 0$ $(1-\alpha)(W + \Delta W_1) - (F_1 - F_2)\beta + R_1 - R_2 - \Delta C - \alpha N_1 + N_2 + K_1 < 0$ $-S + U_2 < 0$	③
$E_6(1,0,1)$	$-\Delta A_2 + A_2 < 0$ $-Q_1 + Q_2 + (1-\alpha)(W + \Delta W_1) - (F_1 - F_2)\beta + R_1 - R_2 - \Delta C - \alpha N_1 + N_2 + K_1 < 0$ $-K_2 - S + U_2 < 0$	④
$E_7(0,1,1)$	$-A_1 + \Delta A_1 < 0$ $-(1-\alpha)(W + \Delta W_1) + (F_1 - F_2)\beta - R_1 + R_2 + \Delta C + \alpha N_1 - N_2 - K_1 < 0$ $-U_1 - S < 0$	⑤
$E_8(1,1,1)$	$A_1 - \Delta A_1 < 0$ $Q_1 - Q_2 - (1-\alpha)(W + \Delta W_1) + (F_1 - F_2)\beta - R_1 + R_2 + \Delta C + \alpha N_1 - N_2 - K_1 < 0$ $-K_2 - U_1 - S < 0$	⑥

5. Result analysis

According to the analysis in Section 4.3, in different situations, the three parties have their own final evolutionary stability strategies. In this study, the group adoption of pure strategy equilibrium point is analyzed. MATLAB software is used to simulate different situations, and the above model is analyzed in depth. The specific parameter settings of 8 situations are shown in Table 4. In addition, in game theory, the initial strategy of one subject is fixed, and the initial strategies of the other two subjects are randomly generated, so as to analyze the influence of the strategies of the other two subjects on the evolution strategy of the subject.

5.1 Scenario simulation under different condition

Table 4. Parameter values

Situation	A_1	A_2	ΔA_1	ΔA_2	K_2	R	Q_2	Q_1	R_1	R_2	ΔC	α
1	1	10	2	3	4	1	5	2	3	3	10	0.5
2	1	**1**	2	3	4	1	5	2	3	3	10	0.5
4	1	10	2	3	4	1	5	2	3	3	10	0.5
6	1	1	2	3	4	1	5	2	3	3	10	0.5
7	1	10	**0.2**	3	4	1	5	2	3	3	10	0.5
8	1	10	**2**	3	4	1	5	2	3	3	10	0.5
Situation	N_1	N_2	W_1	ΔW_1	F_1	F_2	β	K_1	W_2	U_1	U_2	S
1	2	1	2	2	5	1	0.5	3	1	2	9	1
2	2	1	2	2	5	1	0.5	3	1	2	9	1
4	2	1	2	2	5	1	0.5	3	1	2	**0.5**	1
6	2	1	2	2	5	1	0.5	3	1	2	9	**9**
7	2	1	2	2	5	1	0.5	**15**	1	2	0.5	1
8	2	1	2	2	5	1	0.5	5	1	2	9	1

According to the stability analysis of the game model, it could be seen that the choices of the government, new energy vehicle manufacturers and consumers in different stability conditions under the double credit policy are different. In order to study the game model constructed above more intuitively, MATLAB is used for numerical simulation of the strategy combination evolution process under the above six stability conditions in this study. Scenario 1. The evolutionary process of the government (adopt loose regulation), enterprises (not produce NEVs) and consumers (buy traditional fuel vehicles) are shown as follows.

The parameter is set to $A_1 = 1$, $A_2 = 10$, $\triangle A_1 = 2$, $\triangle A_2 = 3$, $K_2 = 4$, $R = 1$, $Q_2 = 5$, $Q_1 = 2$, $R_1 = 3$, $R_2 = 3$, $\triangle C = 10$, $\alpha = 0.5$, $N_1 = 2$, $N_2 = 1$, $W_1 = 2$, $\triangle W_1 = 2$, $F_1 = 5$, $F_2 = 1$, $\beta = 0.5$, $K_1 = 3$, $U_1 = 2$, $U_2 = 9$, $S = 1$, $W_2 = 1$. The initial values of the government, manufacturer and consumer policies are set as $x(0) = 0.5$, $y(0) = 0.5$ and $z(0) = 0.5$. The simulation results are shown in Figure 1.

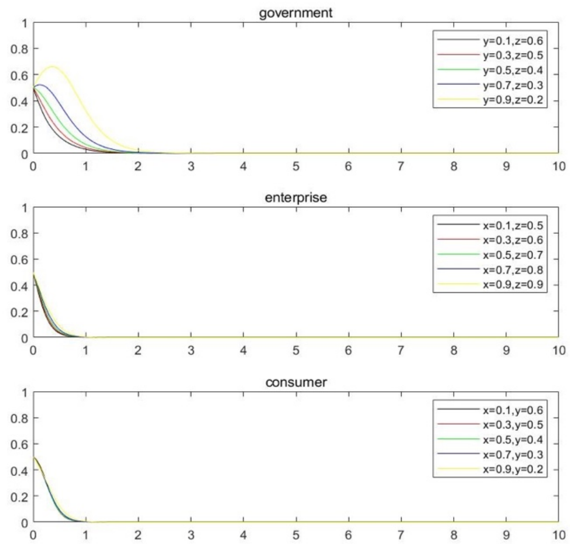

Fig. 1. Evolution path of game subject under stability condition ①

According to Figure 1, it could be seen that if the parameter values meet the stability condition ①. In other words, the cost of the government choosing strict regulation is higher than the benefits and tax collected from strict regulation. The sum of the additional R&D costs paid by enterprises for producing NEVs and the credits they need to pay, minus the profits from selling credits, is higher than the cost of credits purchased for producing traditional fuel vehicles. At the same time, the carbon emission reduction subsidy obtained by consumers buying NEVs is also less than the income obtained by buying traditional fuel vehicles, so the players of the game would tend to choose the strategy of loose regulation, not producing NEVs and buying traditional fuel vehicles respectively. In this case, $(0,0,0)$ is ESS. This indicates that when the cost of strict regulation is too high or the punishment for enterprises producing traditional fuel vehicles is too low, the government will obtain little profit, thus the choice will be loose regulation which reduces the pressure on companies and does not cost extra to develop NEVs, as it is more cost-effective to buy credits directly, so companies choose to produce traditional fuel vehicles. In such a situation, consumers would choose traditional fuel vehicles when the benefits of buying NEVs are less than the disadvantages. In this situation, the main players of the tripartite game take a negative attitude, and the system comes to the worst state. The new energy vehicle industry would not have a better development, and the automobile industry could not make its due contribution to the dual carbon goal.

Scenario 2. The evolutionary process of the government (adopt strict regulation), enterprises (not produce NEVs) and consumers (buy traditional fuel vehicles) are shown as follows.

The parameter is set to $A_1 = 1$, $A_2 = 1$, $\triangle A_1 = 2$, $\triangle A_2 = 3$, $K_2 = 4$, $R = 1$, $Q_2 = 5$, $Q_1 = 2$, $R_1 = 3$, $R_2 = 3$, $\triangle C = 10$, $\alpha = 0.5$, $N_1 = 2$, $N_2 = 1$, $W_1 = 2$, $\triangle W_1 = 2$, $F_1 = 5$, $F_2 = 1$, $\beta = 0.5$, $K_1 = 3$, $U_1 = 2$, $U_2 = 9$, $S = 1$, $W_2 = 1$. Compared with scenario 1, only the cost of strict regulation A_2 is reduced. The initial values of the government, manufacturer and consumer policies are set as $x(0) = 0.5$, $y(0) = 0.5$ and $z(0) = 0.5$. The simulation results are shown in Figure 2.

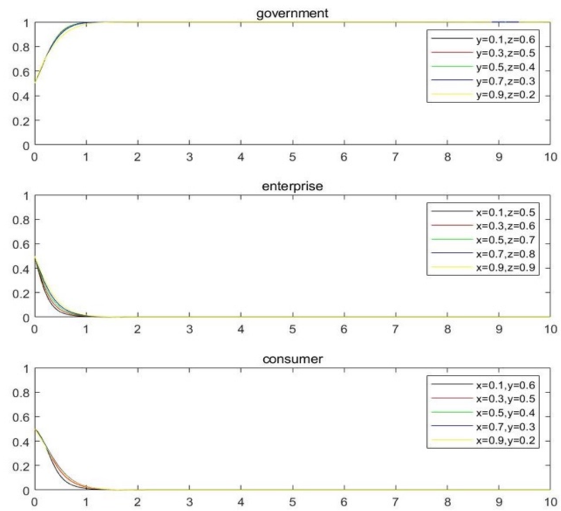

Fig. 2. Evolution path of game subject under stability condition②

According to Figure 2, it could be seen that the stability condition ② is satisfied when the parameter values are taken.

In other words, if the cost to implement strict regulation is less than the benefits and tax revenue gained by strict regulation, the difference between the extra R&D costs of producing NEVs, the need to pay for credits, the losses of the enterprises under strict regulation and the gains gained from the sale of credits is higher than the difference between the costs of credits purchased for producing traditional fuel vehicles. The carbon emission reduction subsidy consumers get when they buy NEVs is smaller than the difference between the income they get and the tax they pay when they choose traditional fuel vehicles. As a result, the tripartite players tend to choose respectively strict regulation, not to produce NEVs and purchase of traditional fuel vehicles. In this case, $(1,0,0)$ is ESS. This shows that as long as the cost of strict regulation is reduced and the government could gain benefits in the governance process, the government would naturally choose strict regulation. While strict government regulation would have an impact on businesses and consumers, it has not improved significantly, so businesses and consumers still prefer traditional fuel vehicles.

Scenario 3. The evolutionary process of the government (adopt loose regulation), enterprises (not produce NEVs) and consumers (buy NEVs) are shown as follows.

The parameter is set to $A_1=1$, $A_2=10$, $\triangle A_1=2$, $\triangle A_2=3$, $K_2=4$, $R=1$, $Q_2=5$, $Q_1=2$, $R_1=3$, $R_2=3$, $\triangle C=10$, $\alpha=0.5$, $N_1=2$, $N_2=1$, $W_1=2$, $\triangle W_1=2$, $F_1=5$, $F_2=1$, $\beta=0.5$, $K_1=3$, $U_1=2$, $U_2=1$, $S=1$, $W_2=1$. Compared with scenario 1, the consumer income U_2 from buying traditional fuel vehicles decreases. The initial values of government, manufacturing and consumer policies are set as $x(0)=0.5$, $y(0)=0.5$ and $z(0)=0.5$. The simulation results are shown in Figure 3.

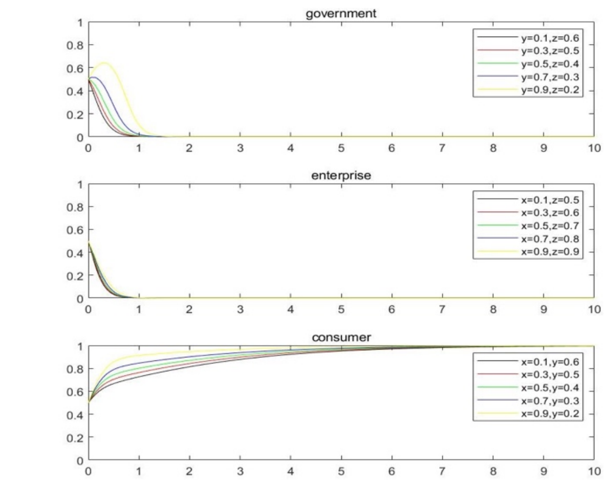

Fig. 3 Evolution path of game subject under stability condition ③

According to Figure 3, it could be seen that the stability condition ③ is satisfied when the parameter values are taken.

In other words, the sum of the costs of strict government regulation and the costs of controlling air pollution is higher than the benefits of strict regulation. The difference between the additional R&D costs paid by the enterprise to produce NEVs, the credits required to pay, and the proceeds obtained from selling credits and NEVs is higher than the difference between the credits required to produce traditional fuel vehicles, the fines paid, and the profits from selling traditional fuel vehicles. Consumers who buy NEVs get more carbon emission reduction subsidies than those buying traditional fuel vehicles. At this time, the tripartite players tend to choose respectively the strategy of loose regulation, not to produce NEVs and traditional fuel vehicles. In this case, $(0,0,1)$ is ESS. This indicates that if there are factors such as rising oil prices, consumers would get less profit from buying traditional fuel vehicles, so they would buy NEVs.

Scenario 4. The evolutionary process of the government (adopt strict regulation), enterprises (not produce NEVs) and consumers (buy NEVs) are shown as follows.

The parameter is set to $A_1=1$, $A_2=1$, $\triangle A_1=2$, $\triangle A_2=3$, $K_2=4$, $R=1$, $Q_2=5$, $Q_1=2$, $R_1=3$, $R_2=3$, $\triangle C=10$, $\alpha=0.5$, $N_1=2$, $N_2=1$, $W_1=2$, $\triangle W_1=2$, $F_1=5$, $F_2=1$, $\beta=0.5$, $K_1=3$, $U_1=2$, $U_2=9$, $S=9$, $W_2=1$. Compared with scenario 2, the government would increase subsidies S for consumers who buy NEVs. The initial values of government, manufacturing and consumer policies are set as $x(0)=0.5$, $y(0)=0.5$ and $z(0)=0.5$. The simulation results are shown in Figure 4.

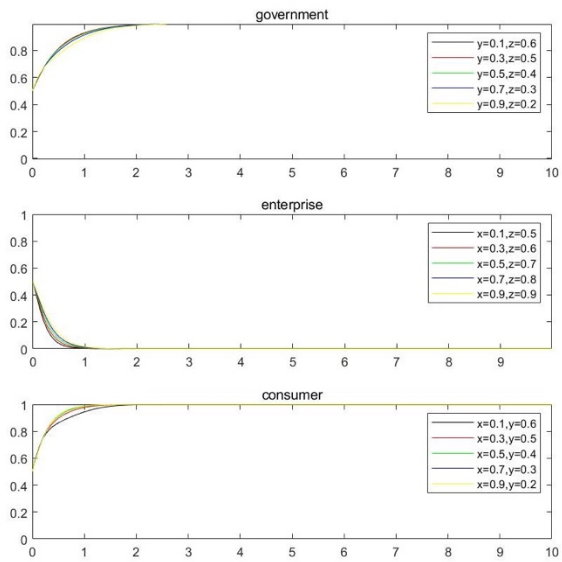

Fig. 4. Evolution path of game subject under stability condition ④

According to Figure 4, it could be seen that the stability condition ④ is satisfied when the parameter values are taken.

In other words, the sum of the costs of strict government regulation and the costs of controlling air pollution is less than the benefits of strict regulation. The additional R&D costs paid by the enterprise to produce NEVs, the required payment of credits, the difference between the losses caused by strict government supervision and the gains from selling NEVs and selling credits are higher than the credits purchased for producing traditional fuel vehicles, the required penalties, and the difference between the losses caused by the enterprise under strict government supervision and the gains from selling traditional fuel vehicles. The sum of the benefits obtained by consumers when purchasing traditional fuel vehicles and the taxes collected by the government is smaller than the carbon emission reduction subsidies obtained when purchasing NEVs. At this time, the tripartite players tend to choose the strategy of strict regulation, not to produce NEVs and to buy traditional fuel vehicles. In this case, $(1,0,1)$ is ESS. Since the government has provided more subsidies to users of NEVs, and buying NEVs is more profitable for consumers, they have turned to support NEVs. However, this change has not had a significant impact on the government and businesses, so the strategic choices for both remain unchanged compared to Scenario 2.

Scenario 5. The evolutionary process of the government (adopt loose regulation), enterprises (produce NEVs) and consumers (buy NEVs) are shown as follows.

The parameter is set to $A_1 = 10$, $A_2 = 10$, $\triangle A_1 = 2$, $\triangle A_2 = 3$, $K_2 = 4$, $R = 1$, $Q_2 = 5$, $Q_1 = 2$, $R_1 = 3$, $R_2 = 3$, $\triangle C = 1$, $\alpha = 0.5$, $N_1 = 2$, $N_2 = 1$, $W_1 = 2$, $\triangle W_1 = 2$, $F_1 = 5$, $F_2 = 1$, $\beta = 0.5$, $K_1 = 3$, $U_1 = 10$, $U_2 = 9$, $S = 1$, $W_2 = 1$. Compared with scenario 4, $\triangle A_1$ decreases, K_1 increases, which means that when the government strictly regulates, the potential revenue obtained by the government decreases and the penalties on traditional fuel vehicle manufacturers to improve their performance increase. The initial values of the government, manufacturer and consumer policies are set as $x(0) = 0.5$, $y(0) = 0.5$ and $z(0) = 0.5$. The simulation results are shown in Figure 5.

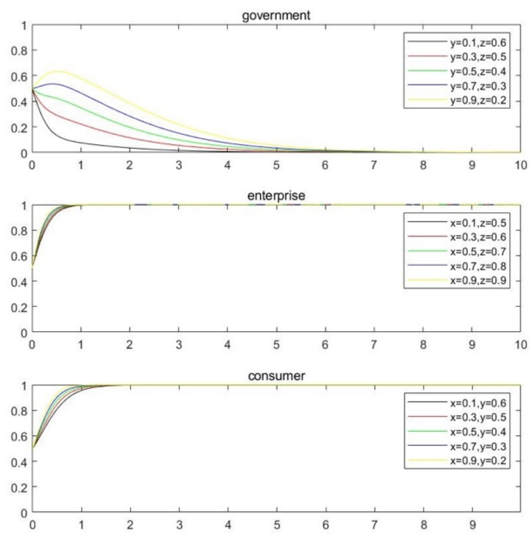

Fig. 5. Evolution path of game subject under stability condition ⑤

According to Figure 5, it could be seen that the stability condition ⑤ is satisfied when the parameter values are taken.

In other words, the cost of strict government regulation is higher than the benefit from it. The difference between the additional research and the development cost to produce NEVs, the credits to be paid, and the revenue from selling the credits and the vehicles is smaller than the difference between the credits to be purchased to produce traditional fuel vehicles, the fines to be paid to the government, and the revenue from selling the vehicles. The sum of the benefits obtained by consumers purchasing NEVs and the carbon emission reduction subsidies granted by the government is positive. At this time, the tripartite players tend to choose the strategy of loose regulation, production of NEVs and purchase of traditional fuel vehicles. In this case, $(0,1,1)$ is ESS. When the government strictly regulates, its contribution to the dual carbon target decreases, so the government still maintains a policy of less strict regulation. However, for enterprises, in order to reduce the atmospheric pollution caused by traditional fuel vehicles and increase the penalties for traditional fuel vehicle manufacturers, the government will choose to produce NEVs so as to respond to the dual carbon goal

Scenario 6. The evolutionary process of the government (adopt strict regulation), enterprises (produce NEVs) and consumers (buy NEVs) are shown as follows.

The parameter is set to $A_1 = 10$, $A_2 = 10$, $\triangle A_1 = 16$, $\triangle A_2 = 3$, $K_2 = 4$, $R = 1$, $Q_2 = 5$, $Q_1 = 2$, $R_1 = 3$, $R_2 = 3$, $\triangle C = 1$, $\alpha = 0.5$, $N_1 = 2$, $N_2 = 1$, $W_1 = 2$, $\triangle W_1 = 2$, $F_1 = 5$, $F_2 = 1$, $\beta = 0.5$, $K_1 = 3$, $U_1 = 10$, $U_2 = 9$, $S = 1$, $W_2 = 1$. Compared with scenario 5, the revenue $\triangle A_1$ obtained by the government from strict governance increases. The initial values of government, manufacturer and consumer policies are set as $x(0) = 0.5$, $y(0) = 0.5$ and $z(0) = 0.5$. The simulation results are shown in Figure 6.

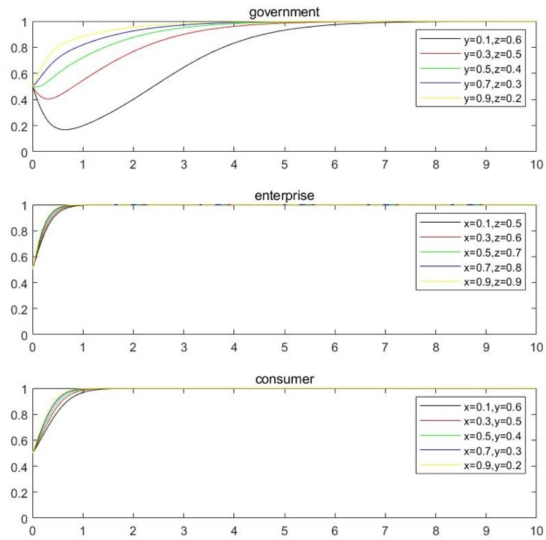

Fig. 6 Evolution path of game subject under the stability condition ⑥

According to Figure 6, it could be seen that the stability condition ⑥ is satisfied when the parameter values are taken.

In other words, the cost of strict government regulation is less than the benefit of strict regulation. The difference between the additional research and development costs paid by the enterprise to produce NEVs, the credits to be paid, and the revenue from selling the credits and the vehicles is smaller than the difference between the credits to be purchased to produce traditional fuel vehicles, the fines to be paid to the government, and the revenue from selling the vehicles. Consumers who purchase NEVs receive government subsidies for carbon emissions reduction, which is higher than the difference between the benefits obtained by purchasing traditional fuel vehicles and the taxes paid. At this time, the tripartite players tend to choose the strategy of strict regulation, produce NEVs and purchase traditional fuel vehicles. In this case, $(1,1,1)$ is ESS. This indicates that when both enterprises and consumers have a positive attitude, the system would come to an optimal cycle state as long as the government gains more revenue in the process of strict regulation, for example, the government's strict regulation is conducive to achieve "carbon peak" and "carbon neutrality" a soon as possible.

6. Discussion

Through the three evolutionary game model and simulation analysis, this study obtained dual credit under the policy of government and automobile manufacturers and consumers. The optimal evolutionary stability strategy, that is, the three parties would eventually achieve (1, 1, 1) a stable state, the government's strict regulation, automobile manufacturers actively produce NEVs, the equilibrium strategies of consumers to purchase NEVs, and these important parameters affecting the selection of all parties are obtained.

(1) According to the simulation results in Section 5.1, this study also shows that the strategic choices of government, manufacturers and consumers would eventually tend to (1, 1, 1), and demonstrates that the strategic choices of all parties would influence each other in the policy implementation process. However, previous studies did not take dual credit policy into account, but only considered subsidy parameters, and generally analyzed the strategic choices of all parties under the subsidy reduction. For example, Zhang and Lu [34] examined the strategies that the government, manufacturing companies and consumers would choose for surveillance, research and development, and the purchase of NEVs in the post-subsidy era. In this study, the relevant costs and benefits of NEVs and CAFC credits are taken into account, and the conclusions obtained are more applicable to existing policies and serve as a guidance for enterprises specifically.

(2) Based on the above discussion, the conditions for the three parties achieving an optimal strategy are obtained. That is, the cost for strict supervision is less than the revenue from strict supervision. The difference between the additional research and development cost, credits to be paid, and revenue from selling the credits and NEVs is smaller than the credits purchased for producing traditional fuel vehicles, the difference between the fines to be paid and the revenue from selling vehicles. Consumers who buy NEVs would receive government subsidies to reduce carbon emissions, which is higher than the difference between income and the tax paid for buying traditional fuel vehicles. In general, the strategic choice of the three parties depends on the total utility obtained by each party, which is conducive to the government for producing NEVs and consumers choosing NEVs.

(3) The cost of strict government regulation and the benefits of reducing carbon emissions, the fines companies have to pay for producing fuel vehicles, the benefits consumers get when buying NEVs, and subsidies for reducing carbon emissions are important factors affecting the decision-making of the three parties. Among them, consumers' willingness to buy NEVs increases when their benefits from buying NEVs and the government's subsidies increase. The contribution of enterprises to reducing carbon emissions in the production of NEVs and the fines they might pay to the government in the production of fuel vehicles are also important factors affecting the decision-making of the three parties. In addition, this study found that government penalties would affect the strategy choice of three parties. The difference lies in that the fine penalty and proportion on the subsidy-fraud enterprises under the government's fiscal subsidy policy imposed on automobile enterprise would affect the choice of automobile enterprise. This study concludes that the fine penalty on the vehicle enterprises with high carbon emission will influence their choices. This is of great significance for the further development of the automobile industry under the dual carbon target.

7. Conclusions

7.1 Main findings

In order to further promote the development of the new energy vehicle industry under the dual credit policy and better contribute to the dual carbon goal, this study established a tripartite evolutionary game model among the government, automobile manufacturers and consumers on the basis of evolutionary game theory so as to study the mutual influence of the three. Through numerical experiments and simulation analysis of the game model, the following conclusions are drawn.

(1) Governments, automobile manufacturers and consumers have different strategic choices under different stability conditions. At the same time, the decisions of the three parties influence each other, and the evolving strategy of one party would be influenced by the main strategies of the other two parties.

(2) If the cost of strict regulation is less than the benefit of which, the additional cost of research and development of NEVs, the pay for credits, benefits from selling the credits and vehicles is less than the difference between credits need to buy for traditional fuel vehicles and fine penalty paying to the government When the government's subsidy for consumers buying NEVs is higher than the difference between the benefits obtained and the tax paid by consumers to buy traditional fuel vehicles, the evolutionary system would reach the ideal state of strict regulation, production of NEVs, purchase of NEVs.

(3) When the cost of strict regulation is reduced or strict regulation is conducive to reducing carbon emissions, the government would choose the strategy of strict regulation. When the government's fine, on enterprises Producing traditional fuel vehicles increases, the enterprises would choose to produce NEVs. When consumers get lower benefits from buying traditional fuel vehicles, but with higher revenues and extra subsidy from buying NEVs, consumers would choose to buy NEVs.

7.2 Limitations and Future Directions

Due to the complexity of the evolutionary game and the limited knowledge of individuals, there are still some shortcomings in this study. First, this study establishes the evolutionary game model of government, automobile manufacturers, and consumers, and conducts simulation analysis. However, this study is lack of the support of actual data and cases, and subsequent research could be combined with real data for quantitative analysis to make the research results more objective and scientific. Secondly, this study does not fully consider other stakeholders, which may have an impact on the game. They could be taken into account in the subsequent modelling process to provide more reliable recommendations for the new energy vehicle industry.

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