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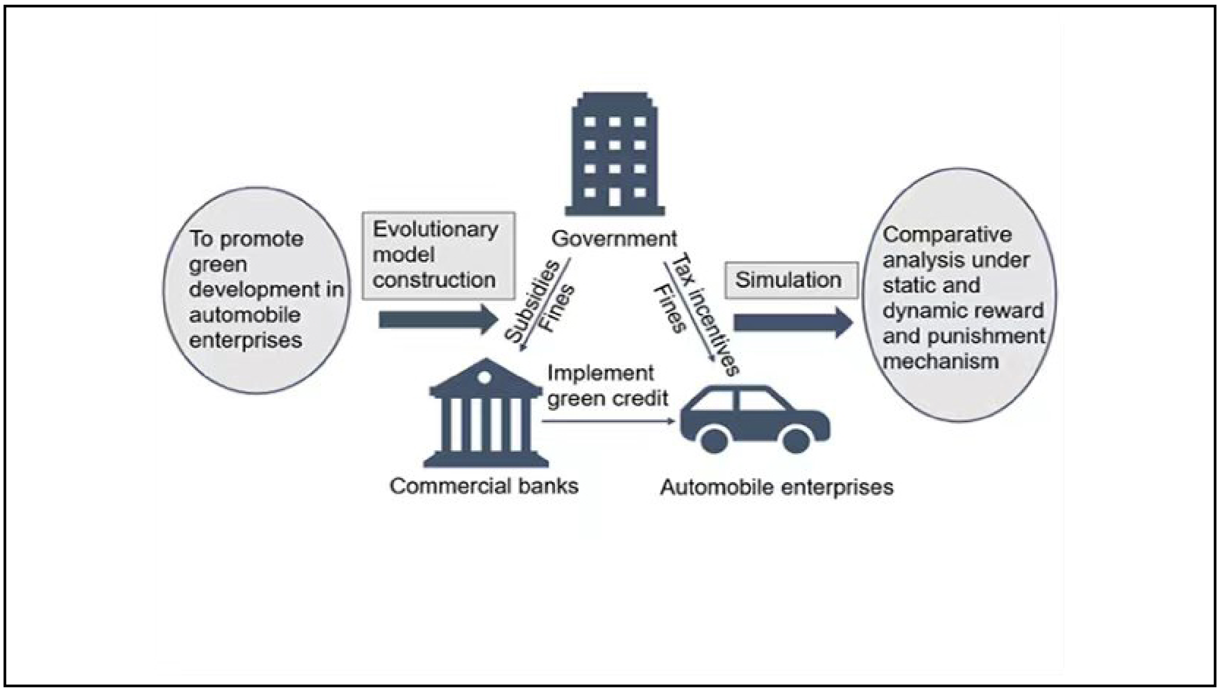
Evolutionary analysis of green credit and automobile enterprises under the mechanism of dynamic reward and punishment based on government regulation

Yu Dong[1,2] ✉, Xiaoyu Huang[1], Hongan Gan[1], and Xuyang Liu[1]

[1]*School of Economics and Management, Anhui University of Science and Technology, Huainan 232001, China;*
[2]*School of Management, University of Science and Technology of China, Hefei 230026, China*

✉Correspondence: Yu Dong, E-mail: ydong@aust.edu.cn

Graphical abstract



Research methods and numerical simulation based on evolutionary model analysis.

Public summary

- This paper constructs a tripartite evolutionary game model among the government, commercial banks, and automobile enterprises, and introduces a dynamic reward and punishment mechanism to explore the evolutionary paths among the three parties.
- Under static reward and punishment, the system is unable to attain a stable equilibrium and the government is in a situation of weak supervision. Under dynamic reward and punishment, the government can achieve efficient supervision of commercial banks and automobile enterprises by adjusting the ceiling of rewards and punishments.
- The implementation of green credit by commercial banks plays a significant role in promoting the green development of automobile enterprises.

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[2]*School of Management, University of Science and Technology of China, Hefei 230026, China*

✉Correspondence: Yu Dong, E-mail: ydong@aust.edu.cn

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Abstract: To explore the green development of automobile enterprises and promote the achievement of the "dual carbon" target, based on the bounded rationality assumptions, this study constructed a tripartite evolutionary game model of government, commercial banks, and automobile enterprises; introduced a dynamic reward and punishment mechanism; and analyzed the development process of the three parties' strategic behavior under the static and dynamic reward and punishment mechanism. *Vensim PLE* was used for numerical simulation analysis. Our results indicate that the system could not reach a stable state under the static reward and punishment mechanism. A dynamic reward and punishment mechanism can effectively improve the system stability and better fit real situations. Under the dynamic reward and punishment mechanism, an increase in the initial probabilities of the three parties can promote the system stability, and the government can implement effective supervision by adjusting the upper limit of the reward and punishment intensity. Finally, the implementation of green credit by commercial banks plays a significant role in promoting the green development of automobile enterprises.

Keywords: automobile enterprises; green credit; system dynamics; reward and punishment mechanism
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1 Introduction

The global energy crisis and climate change have been worsening, seriously affecting people's way of life and productivity. The "dual carbon" target was proposed at the 75th session of the United Nations General Assembly. Achieving "carbon peak and carbon neutrality" can lead to an extensive and profound economic and social systemic change[1]. As an emerging strategic industry, the large-scale growth of the new energy vehicle (NEV) industry will effectively reduce the consumption of fossil fuels, alter the energy structure, and reduce environmental pollution, which is an effective way to achieve "carbon peak and carbon neutrality". According to the *New Energy Vehicle Industry Development Plan (2021–2035)*, sales of NEV will account for approximately 20% of all new car sales by 2025, and by 2035, pure electric vehicles will predominate among newly sold vehicles. China's NEV market has become the largest in the world, and NEV sales have ranked first worldwide for seven consecutive years[2]. The NEV production and sales in 2022 reached 7058000 and 7887000, respectively, and increased by 99.1% and 95.6%, respectively, as shown in Fig. 1. These achievements rely on the support and encouragement of national policies. However, excessive reliance on government subsidies will lead to the neglect of innovation and impact the core competitiveness of automobile enterprises. The continuous occurrence of "compensation fraud" has caused a certain degree of disorder to the automobile industry and increased the cost of government supervision[3]. The Ministry of Finance and other four departments have been informed that the subsidy policy will be terminated on December 31, 2022, marking the end of the 13-year "state subsidy" period. The NEV industry will completely eliminate policy dependence and enter the pure market-driven "post-subsidy era".

With the continuous development of NEV, entering the "curve overtaking" phase while also exposing some shortcomings. The situation where core technology is subject to human constraints continues. To make NEV stable and their

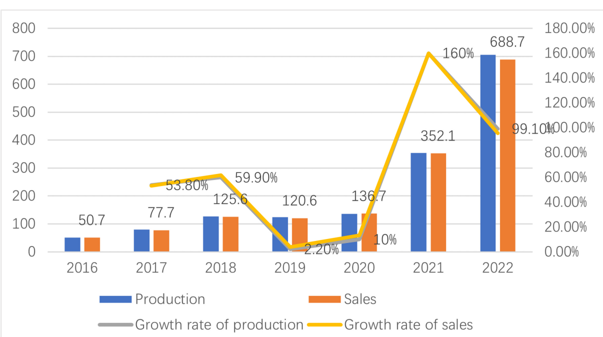

Fig. 1. NEVs' production and sales volume in China (2016–2022).

development healthy, automobile enterprises must make breakthroughs in core technology, and considerable manpower and material investment support for core technological research and innovation are required. As profitable financial organizations, commercial banks can provide green credit to automobile enterprises facing financial difficulties. Green finance helps solve financing difficulties for new energy enterprises and makes it easier to promote the green development of automobile enterprises[4]. Naturally, in contrast to the traditional automobile industry, the NEV industry is a massive systematic project requiring coordinated planning and leadership of the government, as well as combined efforts.

This study constructs a tripartite evolutionary game model for the government, commercial banks, and automobile enterprises; introduces a dynamic reward and punishment mechanism to explore the evolutionary paths among the three parties; and numerically simulates the effects of various parameters on the evolutionary paths and results of the system. The study aims to answer the following questions: ① According to the analysis of evolutionary paths, what are the differences in the dynamic evolution processes of game-players under different reward and punishment mechanisms? ② How can the government act as a regulator and effectively adjust the system stability? It can be concluded from the study that under static reward and punishment, the system is unable to attain a stable equilibrium and the government is in a situation of weak supervision. Under dynamic reward and punishment, the government can achieve efficient supervision of commercial banks and automobile enterprises by adjusting the ceiling of rewards and punishments.

2 Literature review

Scholars worldwide have conducted extensive research on government policies to promote the innovation and development of automobile enterprises. Xu et al.[5] constructed a tripartite evolutionary game model of the government, automobile enterprises, and consumers, and they used the coupling of prospect theory and evolutionary game theory to discuss the impact of new energy promotion policies on the three participants. Fan and Dong[6] compared how governments should choose subsidy strategies to determine whether the diffusion of low-carbon technologies would fluctuate. Zhang and Gai[7] introduced a signal game and concluded that government subsidies should be adjusted according to the different development periods of NEV. Some scholars believed that phasing out of subsidy policies is conducive to the development of a new-energy automobile industry[8]. Wang et al.[9] and Chi et al.[10] found that local industrial policies and government subsidies have incentive effects on enterprise innovation. Xiong and Wang[11] analyzed the incentive effect and difference of “supporting” and “threshold” policies on innovation by using the difference-in-difference method. As a transitional policy, the dual credit policy plays an important role in the new energy industry and has attracted the attention of scholars. Lu et al.[12] studied the influence mechanism of the dual credit policy on fuel vehicles and NEV from the perspective of pricing. Liu et al.[13] studied the influence of the dual credit policy on technological innovation. Li et al.[14] pointed out that such policy can significantly increase the NEV output and has a substitution effect on subsidies. Jiao et al.[15] established a two-stage Stackelberg model and found that subsidies, a dual credit policy, and charging pile construction positively affect NEV popularization. Many studies have concentrated on how subsidies and dual credit policies affect automobile enterprises’ innovation; however, with the withdrawal of subsidies, the question remains as to how should automobile enterprises with financial difficulties survive and develop.

Green credit has become one of the most important economic tools for the development of the real economy. How green credit can help the development of enterprises was studied from two perspectives. First, empirical study on the effect of green credit on enterprises innovation. Ding et al.[16] found that green credit policies can promote green innovation in energy-saving and environmental protection enterprises more effectively. Zhang et al.[17] and Shu et al.[18] empirically tested the relationship between green credit and innovation performance. Zhang et al.[19] found that green credit can improve environmental quality by promoting corporate innovation. Huang et al.[20] believed that green credit could effectively reduce the financing costs of environmental protection enterprises, including NEV enterprises, and promote their healthy development. The second is a game analysis of the effect of green credit on enterprise behavior. Zhu et al.[21] constructed a stochastic evolutionary game model for local governments, commercial banks, and lending enterprises, and put forward some suggestions for optimizing the green credit mechanism. Feng et al.[22] constructed a tripartite evolutionary game model of government, coal power enterprises, and banks and expounded on the key factors and mechanisms of green transformation of coal power enterprises. Zhou et al.[23] constructed an evolutionary model and empirically studied the strategy choices and evolutionary paths of game-players before and after the implementation of the green credit policy.

Some scholars have used game theory to analyze the game processes of multiple entities in automobile enterprises. Wu et al.[24] constructed a tripartite evolutionary model of industry, university, and research and analyzed strategic selection in the collaborative innovation process. Liu et al.[25] aimed to address the serious asymmetry of information on new energy vehicles, using the Bayesian dynamic game model to study the relationship between manufacturers, consumers, and the government. Ma et al.[26] established a two-stage dynamic game model and studied the technological innovation of duopoly enterprises in the new-energy automobile industry.

In contrast to classical games, evolutionary game theory studies the dynamic process by which an agent’s behavioral strategies change with time without requiring complete rationality or complete information[27]. Recently, evolutionary games have been widely used to study the innovation and development of automobile enterprises. However, some deficiencies remain in the existing research. Most of these studies have focused on static parameter analysis, and only a few scholars have considered dynamic parameter analysis. Jin et al.[28] introduced a dynamic dual credit policy to explore its impact on the development of NEV. He and Sun[29] demonstrated that NEV consumers and manufacturers can

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engage in the recycling of power batteries using dynamic rewards and punishments. Entering the "post-subsidy era", where should the green development of automobile companies with financial difficulties go? Owing to information asymmetry and opacity, it is necessary to discuss whether commercial banks will be willing to implement green credit to help the development of automobile enterprises, whether automobile enterprises will engage in "loan fraud" behavior detrimental to the interests of commercial banks and the environment, and the measures the government should take to deal with these situations.

The potential contributions of this study are as follows: First, by constructing a tripartite evolutionary game model of government, commercial banks, and automobile enterprises and introducing a dynamic reward and punishment mechanism, it points to the strategy choice and evolutionary paths of game players and expands the micro path of green development of automobile enterprises. Second, under the withdrawal of subsidy policy, this study provides a new perspective on how the government should take measures to promote the green development of automobile enterprises, so as to better promote the realization of the goal of "carbon neutrality".

3 Methods

3.1 Model assumption

Hypothesis 1. The three parties are bounded rational participants and aim to maximize their own interests. In the evolutionary process, the information of the three parties is asymmetrical, and they must constantly learn and refine their own strategies to achieve an optimal strategy in the game process. Three participants will play repeated games based on the benefits and costs.

Hypothesis 2. The government's strategic space is supervision/non-supervision. When the government chooses supervision, measures should be taken to promote the green development of automobile enterprises, such as a fuel tax, purchase tax, and license plate lottery. The government must pay the cost of supervision B_1, and it should provide subsidies S_1 to commercial banks that implement green credit, and impose fines F_1 for commercial banks that did not implement green credit when producing NEVs. When automobile enterprises produce NEVs, the government provides environmental tax incentives S_2. In this case, the government gains additional income R by enhancing credibility; simultaneously, when the automobile enterprises produce fuel vehicles (FVs), the government imposes fines F_2. When the government chooses non-supervision, just relying on the role of the market to allocate resources, if the automobile enterprises do not produce NEVs, the government will have to pay cost B_2 for environmental governance.

Hypothesis 3. The strategic space for commercial banks is to implement green credit or not. Commercial banks can choose to implement green credit according to their national policies and business needs. The commercial banks' revenue from implementing green credit is E_1 when automobile enterprises produce NEVs. If the automobile enterprises show the behavior of loan fraud, commercial banks' revenue is E_2; simultaneously, commercial banks need to assess and supervise automobile enterprises regularly and pay a certain amount of time and labor costs T.

Hypothesis 4. The strategic space for automobile enterprises is NEVs/FVs. Automobile enterprises can choose whether to invest a certain amount of innovation costs to produce NEVs. We assume that NEVs and FVs have different performances, and that the unit production cost of NEV is c_1, the unit production cost of FV is c_2 ($c_1 > c_2$), the sales prices of NEV, and the FV are p_1 and p_2 ($p_1 > p_2$). When automobile enterprises use green credit to produce NEVs, the profit obtained by saving capital costs is r_1, and the profit obtained by producing FVs is r_2 ($r_1 > r_2$). These variables are presented in Table 1.

3.2 Hotelling demand

We assume that the consumers are willing to purchase only one product unit. NEVs and FVs compete for the marginal consumers. NEVs are located at the 0 end of the line, and FVs are located at the 1 end of the line segment. The consumers are located at the x_1 position between the line segment [0, 1]. To obtain a satisfactory product, consumers need to spend the cost t to purchase the product in the area where it is sold, the cost of purchasing an NEV will be tx_1, and the cost of purchasing an FV will be $t(1-x_1)$. Supposing the basic utility of NEV and FV is u_1 and u_2, the emission reduction levels of NEV and FV are e_1 and e_2 ($e_1 > e_2$), and the consumer's preference for low-carbon emission reduction is $\alpha(\alpha > 0)$, A represents the utility obtained from purchasing a NEV, and B represents the potential cost of purchasing a FV. The utility for consumers can be obtained as follows:

$$\begin{cases} U_{c1} = u_1 + \alpha e_1 - p_1 - tx_1 + A, \\ U_{c2} = u_2 + \alpha e_2 - p_2 - t(1-x_1) - B. \end{cases} \tag{1}$$

If the consumer's low-carbon preference is undifferentiated, and its location is x^*, then its utility is the same wherever the consumer makes a purchase, x^* should meet

Table 1. Variable description.

Variable	Description
R	Additional revenues for government in supervision
S_1	Government subsidies for commercial banks implementing green credit
S_2	Environmental tax incentives for automobile enterprises producing NEVs
B_1	Government supervision costs
B_2	Government environmental governance costs
E_1	Green credit revenues when automobile enterprises produce NEVs
E_2	Green credit revenues when automobile enterprises produce FVs
T	The costs of implementing green credit in commercial banks
π_1	Profits of automobile enterprises producing NEVs
π_2	Profits of automobile enterprises producing FVs
r_1	Profits from using green credit to produce NEVs
r_2	Profits from using green credit to produce FVs
F_1	Government fines on commercial banks
F_1	Government fines on automobile enterprises

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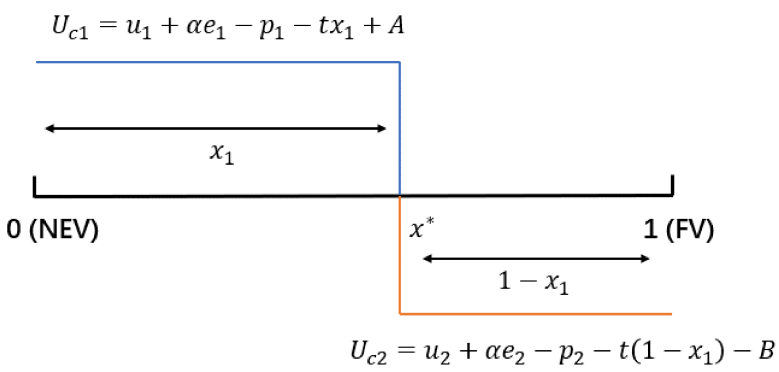

Fig. 2. Market shares of NEVs and FVs.

$$u_1 + \alpha e_1 - p_1 - tx^* + A = u_2 + \alpha e_2 - p_2 - t(1 - x^*) - B. \quad (2)$$

By solving Eq. (2),

$$x^* = ((u_1 - u_2) + \alpha(e_1 - e_2) + (p_2 - p_1) + t + A + B)/(2t),$$

the consumers distributed in [0, x^*] will choose to purchase NEVs, and those distributed in [x^*, 1] will purchase FVs, as shown in Fig. 2. The profit functions of automobile enterprises that produce NEVs and FVs can be obtained as:

$$\begin{cases} \pi_1 = (p_1 - c_1)\dfrac{(u_1 - u_2) + \alpha(e_1 - e_2) + (p_2 - p_1) + t + A + B}{2t}, \\ \pi_2 = (p_2 - c_2)\dfrac{t - (u_1 - u_2) - \alpha(e_1 - e_2) - (p_2 - p_1) - A - B}{2t}. \end{cases} \quad (3)$$

Let $\dfrac{\partial \pi_1}{\partial p_1} = 0$, $\dfrac{\partial \pi_2}{\partial p_2} = 0$, it is concluded that

$$\begin{cases} p_1 = \dfrac{(u_1 - u_2) + \alpha(e_1 - e_2) + p_2 + t + A + B + c_1}{2}, \\ p_2 = \dfrac{t - (u_1 - u_2) - \alpha(e_1 - e_2) + p_1 - A - B + c_2}{2}. \end{cases} \quad (4)$$

Substituting into p_1, p_2:

$$\begin{cases} \pi_1 = \dfrac{[(u_1 - u_2) + \alpha(e_1 - e_2) + 3t + A + B + c_2 - c_1]^2}{18t}, \\ \pi_2 = \dfrac{[(u_2 - u_1) + \alpha(e_2 - e_1) + 3t - A - B + c_1 - c_2]^2}{18t}. \end{cases} \quad (5)$$

3.3 Model construction

The participants make choices based on their own wishes and aim to maximize their interests in the game model. For the government, the probability of choosing the supervision strategy is x, and the probability of choosing the nonsupervision strategy is $1 - x$; for the commercial banks, the probability of implementing green credit is y, and the probability of not implementing green credit is $1 - y$; for the automobile enterprises, the probability of producing NEVs is z, and the probability of producing FVs is $1 - z$. $x, y, z \in [0, 1]$. Based on these assumptions, the game payment matrix for the government, commercial banks, and automobile enterprises is shown in Table 2. The tripartite stakeholder decision tree is shown in Fig. 3.

Table 2. Payment matrix of government, commercial banks, and the automobile enterprises.

Government	Commercial banks	Automobile enterprises	
		NEV	FV
Supervision	Implement green credit	$R - B_1 - S_1 - S_2$	$-B_1 - B_2 - S_1 + F_2$
		$E_1 + S_1 - T$	$E_2 + S_1 - T$
		$\pi_1 + S_2 + r_1$	$\pi_2 - F_2 + r_2$
	Do not implement green credit	$R - B_1 - S_2 + F_1$	$-B_1 - B_2 + F_2$
		$-F_1$	0
		$\pi_1 + S_2$	$\pi_2 - F_2$
Nonsupervision	Implement green credit	0	$-B_2$
		$E_1 - T$	$E_2 - T$
		$\pi_1 + r_1$	$\pi_2 + r_2$
	Do not implement green credit	0	$-B_2$
		0	0
		π_1	π_2

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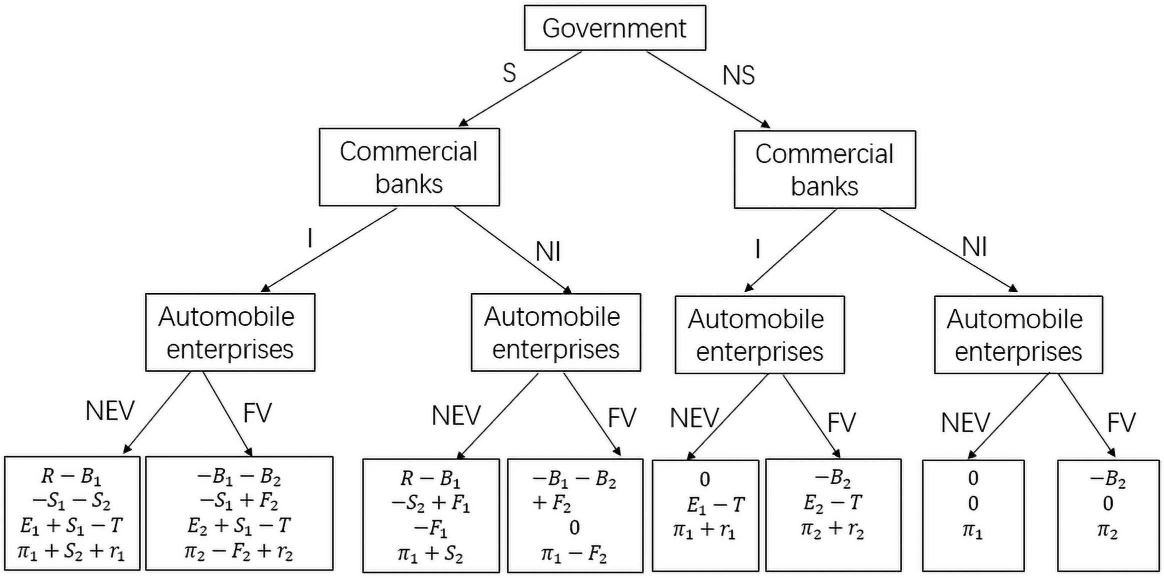

Fig. 3. Tripartite stakeholder decision tree.

4 Tripartite evolutionary model analysis

4.1 Government game equilibrium analysis

According to Table 2, the expected payoff of the government that chooses to supervise is U_1, the expected payoff of choosing nonsupervision is U_2, and the average payoff is $\bar{U}$.

$$U_1 = yz(R-B_1-S_1-S_2)+y(1-z)(-B_1-B_2-S_1+F_2)+(1-y)z(R-B_1-S_2+F_1)+(1-y)(1-z)(-B_1-B_2+F_2), \tag{6}$$

$$U_2 = y(1-z)(-B_2)+(1-y)(1-z)(-B_2), \tag{7}$$

$$\bar{U} = xU_1+(1-x)U_2. \tag{8}$$

The replicator dynamic equation that government chooses to supervise is:

$$F(x) = \frac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)\cdot[y(-S_1)+z(R-S_2+F_1-F_2)+yz(-F_1)-B_1+F_2]. \tag{9}$$

Derive $F(x)$ to obtain:

$$F'(x) = (1-2x)\cdot[y(-S_1)+z(R-S_2+F_1-F_2)+yz(-F_1)-B_1+F_2]. \tag{10}$$

According to the differential stability theorem, when $F(x)=0$ and $\frac{\mathrm{d}F(x)}{\mathrm{d}x}<0$, x is the evolutionarily stable strategy (ESS).

When $[y(-S_1)+z(R-S_2+F_1-F_2)+yz(-F_1)-B_1+F_2]=0$, $F(x)\equiv 0$, indicating that the government's strategic choices do not change over time. When $[y(-S_1)+z(R-S_2+F_1-F_2)+yz(-F_1)-B_1+F_2]\neq 0$, $x=0$ and $x=1$ are two possible ESS. Let $\bar{z}=\frac{B_1-F_2-y(-S_1)}{(1-y)F_1+R-S_2-F_2}$, if $z<\bar{z}$, $x=0$ is the ESS; if $z>\bar{z}$, $x=1$ is the ESS. According to the above analysis, a three-dimensional dynamic evolution trend of the government can be obtained, as shown in Fig. 4a.

Through the analysis, it can be found that when R and F_1 increase, $\bar{z}$ decreases. This indicates that the greater the benefits obtained, the greater the fines imposed, and the more the government is inclined to implement the strategy of supervision. When the supervision costs and subsidies and environmental tax incentives increase, $\bar{z}$ also increases, and the government is more inclined to choose the nonsupervision strategy.

4.2 Commercial banks game equilibrium analysis

According to Table 2, the expected payoff of the commercial banks that choose to implement green credit is V_1, the expected payoff of choosing not to implement green credit is V_2, and the average payoff is $\bar{V}$.

$$V_1 = xz(E_1+S_1-T)+(1-x)z(E_1-T)+x(1-z)(E_2+S_1-T)+(1-x)(1-z)(E_2-T), \tag{11}$$

$$V_2 = xz(-F_1), \tag{12}$$

$$\bar{V} = yV_1+(1-y)V_2. \tag{13}$$

The replicator dynamic equation that commercial banks choose to implement green credit is:

$$F(y) = \frac{\mathrm{d}y}{\mathrm{d}t} = y(1-y)[xS_1+z(E_1-E_2)+xzF_1+E_2-T]. \tag{14}$$

Derive $F(y)$ to obtain:

$$F'(y) = (1-2y)[xS_1+z(E_1-E_2)+xzF_1+E_2-T]. \tag{15}$$

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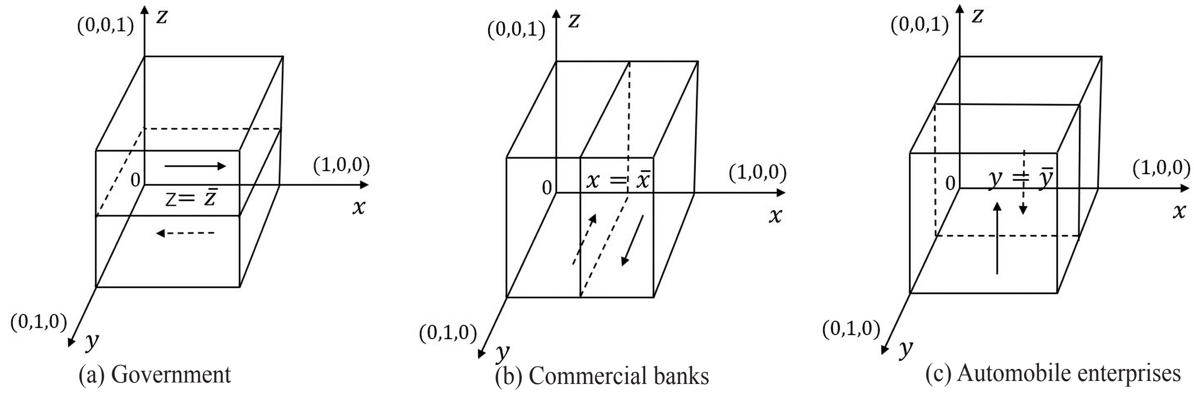

Fig. 4. Tripartite replication of dynamic phase diagram.

According to the differential stability theorem, when $F(y)=0$ and $\frac{\mathrm{d}F(y)}{\mathrm{d}y}<0$, y is the ESS.

When $[xS_1+z(E_1-E_2)+xzF_1+E_2-T]=0$, $F(y)\equiv 0$, indicating that the strategic choice of commercial banks at this time does not change with time. When $[xS_1+z(E_1-E_2)+xzF_1+E_2-T]\neq 0$, $y=0$ and $y=1$ are two possible ESS. Let $\bar{x}=\frac{T-E_2-z(E_1-E_2)}{zF_1+S_1}$, if $x<\bar{x}$, $y=0$ is the ESS; if $x>\bar{x}$, $y=1$ is the ESS. Based on the above analysis, the three-dimensional dynamic evolution trend of commercial banks can be obtained, as shown in Fig. 4b.

Through the analysis, it can be found that when S_1 and F_1 increase, $\bar{x}$ decreases, this indicates that the greater subsidies obtained, the greater the fines imposed, and commercial banks are more inclined to implement green credit. The greater the cost of implementing green credit, the lower the willingness of commercial banks to do so.

4.3 Automobile enterprises game equilibrium analysis

According to Table 2, the expected payoff of the automobile enterprises that produce NEVs is W_1, the expected payoff of producing FVs is W_2, and the average payoff is $\bar{W}$.

$$W_1=xy(\pi_1+S_2+r_1)+(1-x)y(\pi_1+r_1)+x(1-y)(\pi_1+S_2)+(1-x)(1-y)(\pi_1), \tag{16}$$

$$W_2=xy(\pi_2-F_2+r_2)+(1-x)y(\pi_2+r_2)+x(1-y)(\pi_2-F_2)+(1-x)(1-y)(\pi_2), \tag{17}$$

$$\bar{W}=zW_1+(1-z)W_2. \tag{18}$$

The replicator dynamic equation that automobile enterprises choose to produce NEVs is

$$F(z)=\frac{\mathrm{d}z}{\mathrm{d}t}=z(1-z)[x(S_2+F_2)+y(r_1-r_2)+\pi_1-\pi_2]. \tag{19}$$

Derive $F(z)$ to obtain

$$F'(z)=(1-2z)[x(S_2+F_2)+y(r_1-r_2)+\pi_1-\pi_2]. \tag{20}$$

According to the differential stability theorem, when $F(z)=0$ and $\frac{\mathrm{d}F(z)}{\mathrm{d}z}<0$, z is the ESS.

When $[x(S_2+F_2)+y(r_1-r_2)+\pi_1-\pi_2]=0$, $F(z)\equiv 0$, indicating that the strategic choice of automobile enterprises at this time does not change with time. When $[x(S_2+F_2)+y(r_1-r_2)+\pi_1-\pi_2]\neq 0$, $z=0$ and $z=1$ are two possible ESS. Let $\bar{y}=\frac{\pi_2-\pi_1-x(S_2+F_2)}{r_1-r_2}$, if $y<\bar{y}$, $z=0$ is the ESS; if $y>\bar{y}$, $z=1$ is the ESS. Based on the above analysis, the three-dimensional dynamic evolution trend of automobile enterprises can be obtained, as shown in Fig. 4c.

The analysis shows that when $\pi_2-\pi_1$ increases, $\bar{y}$ increases, indicating that the greater the profits gap, the more automobile enterprises are inclined to produce FVs. When x increases, $\bar{y}$ decreases, indicating that automobile enterprises tend to produce NEVs. This suggests that the government's supervision directly impacts the strategic choice of automobile enterprises. The greater the fines and tax incentives imposed, $\bar{y}$ decreases, and the more automobile enterprises are inclined to produce NEVs. When r_1-r_2 increases, $\bar{y}$ decreases, and the higher the willingness of automobile enterprises to produce NEVs.

4.4 Equilibrium analysis of the tripartite evolutionary system

According to the replication dynamic equation of the government, commercial banks and automobile enterprises can construct a Jacobian matrix. The tripartite evolutionary stability trend and related factors affecting the evolutionary stability state can be obtained by analyzing the local stability of the Jacobian matrix in the evolutionary system[30]. The Jacobian matrix of the system is:

$$J=\begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}. \tag{21}$$

Calculation process of Jacobian matrix:

$$\frac{\partial F(x)}{\partial x}=(1-2x)[y(-S_1)+z(R-S_2+F_1-F_2)+yz(-F_1)-B_1+F_2], \tag{22}$$

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$$\frac{\partial F(x)}{\partial y} = x(1-x)[z(-F_1)-S_1], \tag{23}$$

$$\frac{\partial F(x)}{\partial z} = x(1-x)[y(-F_1)+R-S_2+F_1-F_2], \tag{24}$$

$$\frac{\partial F(y)}{\partial x} = y(1-y)(zF_1+S_1), \tag{25}$$

$$\frac{\partial F(y)}{\partial y} = (1-2y)[xS_1+z(E_1-E_2)+xzF_1+E_2-T], \tag{26}$$

$$\frac{\partial F(y)}{\partial z} = y(1-y)(xF_1+E_1-E_2), \tag{27}$$

$$\frac{\partial F(z)}{\partial x} = z(1-z)(S_2+F_2), \tag{28}$$

$$\frac{\partial F(z)}{\partial y} = z(1-z)(r_1-r_2), \tag{29}$$

$$\frac{\partial F(z)}{\partial z} = (1-2z)[x(S_2+F_2)+y(r_1-r_2)+\pi_1-\pi_2]. \tag{30}$$

In an asymmetric game, if the information asymmetry condition holds true, the evolutionarily stable strategy is pure strategy[31]. Let $F(x)=0$, $F(y)=0$, $F(z)=0$, then, eight pure strategy equilibrium points can be obtained. According to Lyapunov's first law, if the eigenvalues of the Jacobian matrix of each equilibrium point are all negative, the equilibrium point is an evolutionarily stable strategy of the game system. Accordingly, eight equilibrium points were introduced into the Jacobian matrix, and the eigenvalues of the eight equilibrium points are calculated, as shown in Table 3.

Proposition 1. Given the condition $R>S_1+S_2+B_1$, $F_1+S_1+E_1-T>0$, $\pi_1+r_1+S_2>\pi_2+r_2-F_2$, the evolutionary game eventually evolves to the ideal state $(1,1,1)$.

Proposition 1 suggests that when the additional benefits for the government in supervision are greater than the subsidies for commercial banks and the environmental tax incentives for automobile enterprises and supervision costs, the government chooses to supervise. When the actual benefits of commercial banks are greater than zero, they choose to implement green credit as a for-profit organization. When the actual benefits obtained from NEV production are greater than those obtained from FV production, automobile enterprises choose to produce NEVs. To further explore this situation, a system dynamics model was introduced to describe the behavioral changes among the three parties over time.

5 Numerical simulation analysis

To verify the reliability of the model and observe the evolutionary trajectories of different strategies more intuitively, this study uses *Vensim PLE* for numerical simulation analysis to study the strategic selection of tripartite. Let $x=0.5$, $y=0.5$, $z=0.5$ as the initial probability. The initial time of evolution is 0, and the end time is 100.

The government's ratio of the cost of supervision to the environmental tax incentives for automobile enterprises is $B_1:S_2=0.2:1$[32]. Checking the balance of green credit held by the Industrial and Commercial Bank of China at the end of 2019, 2020, 2021, and 2022, according to the relevant policy papers of *Several Measures to Promote the Development of Green Finance in Xiamen City* shows the execution of incremental incentives for green credit is rewarded with 0.02% of the green credit increment in the year. Taking BYD (Build Your Dreams) Auto as an example, the prices of its NEV and FV are ¥276300 and ¥165800, respectively, assuming that the emission reduction level of the NEV is 20% less than that of the FV[33]. The other parameters are set based on this relationship.

5.1 Simulation analysis of static reward and punishment mechanism

To achieve the ideal state, that is, the government chooses to supervise, commercial banks implement green credit, and automobile enterprises produce NEVs. According to Table 3, the parameters need to be meet $R>S_1+S_2+B_1$, $F_1+S_1+E_1-T>0$, $\pi_1+r_1+S_2>\pi_2+r_2-F_2$. Let $R=3.5$, $S_1=1.8$, $B_1=0.2$, $E_1=7$, $S_2=1$, $E_2=6.1$, $F_1=0.7$, $\pi_1=5.3$, $\pi_2=7.8$, $r_1=2.313$, $r_2=0.27$, $F_2=1.022$, $T=7.5$. The simulation results are presented in Fig. 5. Under the initial conditions above, the tripartite evolution reaches an ideal state $(1,1,1)$.

Let $F(x)=0$, $F(y)=0$, $F(z)=0$; then, the eight pure-strategy equilibrium points can be obtained, when

Table 3. System equilibrium points and eigenvalues.

Equilibrium points	Eigenvalues λ_1	Eigenvalues λ_2	Eigenvalues λ_3
$E_1(0,0,0)$	$-B_1+F_2$	E_2-T	$\pi_1-\pi_2$
$E_2(0,0,1)$	$R-S_2-B_1+F_1$	E_1-T	$-(\pi_1-\pi_2)$
$E_3(0,1,0)$	$-S_1-B_1+F_2$	$-(E_2-T)$	$r_1-r_2+\pi_1-\pi_2$
$E_4(0,1,1)$	$-S_1+R-S_2-B_1$	$-(E_1-T)$	$-(r_1-r_2+\pi_1-\pi_2)$
$E_5(1,0,0)$	$-(-B_1+F_2)$	S_1+E_2-T	$S_2+F_2+\pi_1-\pi_2$
$E_6(1,0,1)$	$-(R-S_2-B_1+F_1)$	$S_1+E_1+F_1-T$	$-(S_2+F_2+\pi_1-\pi_2)$
$E_7(1,1,0)$	$-(-S_1-B_1+F_2)$	$-(S_1+E_2-T)$	$S_2+F_2+r_1-r_2+\pi_1-\pi_2$
$E_8(1,1,1)$	$-(-S_1+R-S_2-B_1)$	$-(F_1+S_1+E_1-T)$	$-(S_2+F_2+r_1-r_2+\pi_1-\pi_2)$

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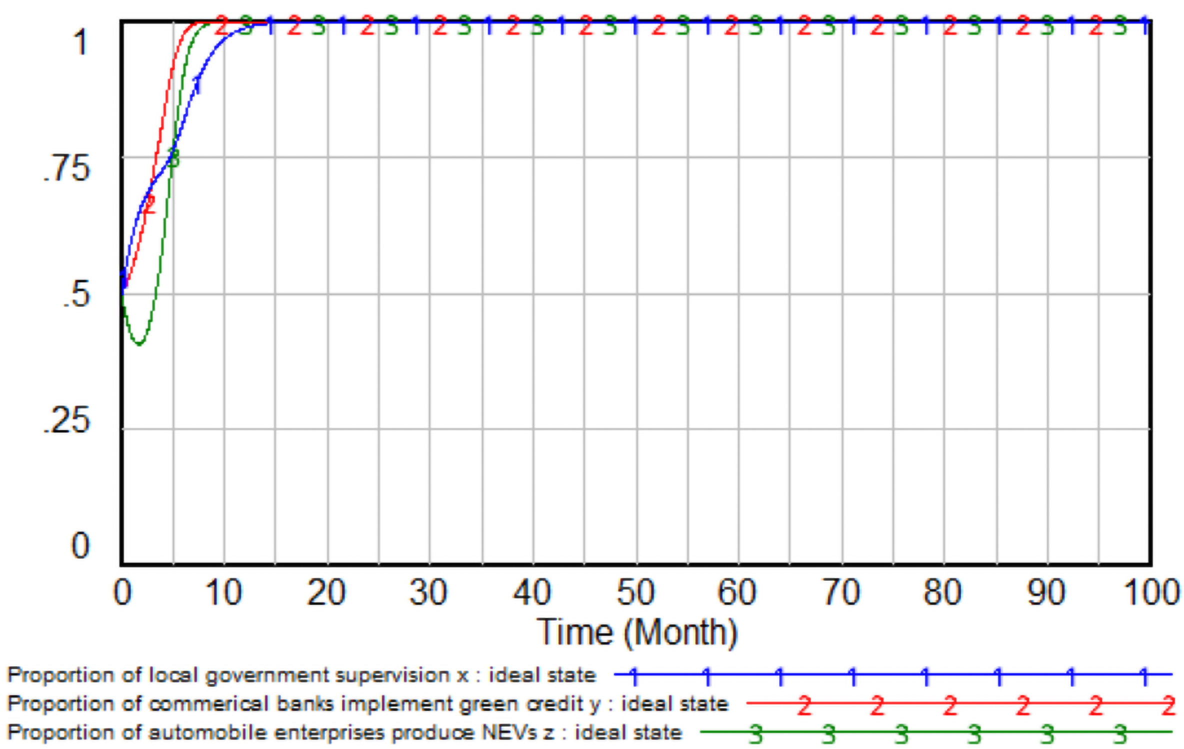

Fig. 5. Evolutionary trajectory in the ideal state.

$$0 < \frac{T - E_2 - z(E_1 - E_2)}{zF_1 + S_1} < 1,$$

$$0 < \frac{\pi_2 - \pi_1 - x(S_2 + F_2)}{r_1 - r_2} < 1,$$

$$0 < \frac{B_1 - F_2 - y(-S_1)}{(1-y)F_1 + R - S_2 - F_2} < 1,$$

there is another equilibrium point $(\bar{x}, \bar{y}, \bar{z})$ in the system, in meeting $0 < T - E_2 - z(E_1 - E_2) < zF_1 + S_1$, $0 < \pi_2 - \pi_1 - x(S_2 + F_2) < r_1 - r_2$, $(1-y)F_1 + R - S_2 - F_2 > 0$, $F_2 < B_1 - y(-S_1) < (1-y)F_1 + R - S_2$. Let $R = 3$, $S_1 = 1.8$, $B_1 = 0.2$, $E_1 = 7$, $S_2 = 1.032$, $E_2 = 6.1$, $F_1 = 0.7$, $\pi_1 = 5.3$, $\pi_2 = 7.8$, $r_1 = 2.313$, $r_2 = 0.27$, $F_2 = 1.022$, $T = 7.5$. The simulation result is shown in Fig. 6.

As shown in Fig. 6, the evolutionary trajectories of the government, commercial banks, and automobile enterprises fluctuate continuously, and are unable to converge to a stable value or reach a stable state. Over time, as the amplitude of the tripartite fluctuations increases, the more unstable it becomes. The choice of strategy at this point affects the returns of the tripartite entities, which are all bounded rational entities and are required to continuously learn and modify their strategies throughout evolution, resulting in a state of tripartite volatility.

5.2 Simulation analysis of dynamic reward and punishment mechanism

The above analysis shows that the system cannot achieve stability under static reward and punishment mechanisms. Furthermore, the system stability is simulated and analyzed under the dynamic reward and punishment mechanism.

5.2.1 System dynamics model construction

Based on the establishment of the three-party replication dynamic equation in the previous section, the system dynamics model of the government, commercial banks, and automobile enterprises is constructed using the *Vensim PLE* software, which mainly comprises three rate variables, three level variables, and twenty auxiliary variables. The SD model is shown in Fig. 7.

Let $S_1 = (1-y)s_1$, $S_2 = (1-z)s_2$, $F_1 = (1-y)f_1$, $F_2 = (1-z)f_2$; where s_1, s_2 are the government reward ceilings for commercial banks and automobile enterprises; f_1, f_2 are the government punishment ceilings for commercial banks and automobile enterprises.

Under the reward mechanism, at the early stage of the government's implementation of the reward, fewer commercial banks and automobile enterprises choose to implement green credit and produce NEVs. To reduce environmental pollution, the government will increase the reward to encourage commercial banks to help automobile enterprises carry out technological innovation. However, as more commercial banks and automobile enterprises make strategic choices more actively, the reward will decrease if the government meets or exceeds its emission reduction targets. Therefore, government rewards are inversely proportional to the probabilities of commercial banks implementing green credit and of automobile enterprises producing NEVs. And under this punishment mechanism, commercial banks choose not to implement green credit and automobile enterprises choose to produce FVs, that is, when y and z decrease, $(1-x)$ and $(1-z)$ increase, the fines imposed on commercial banks and automobile enterprises will also increase. Government fines for

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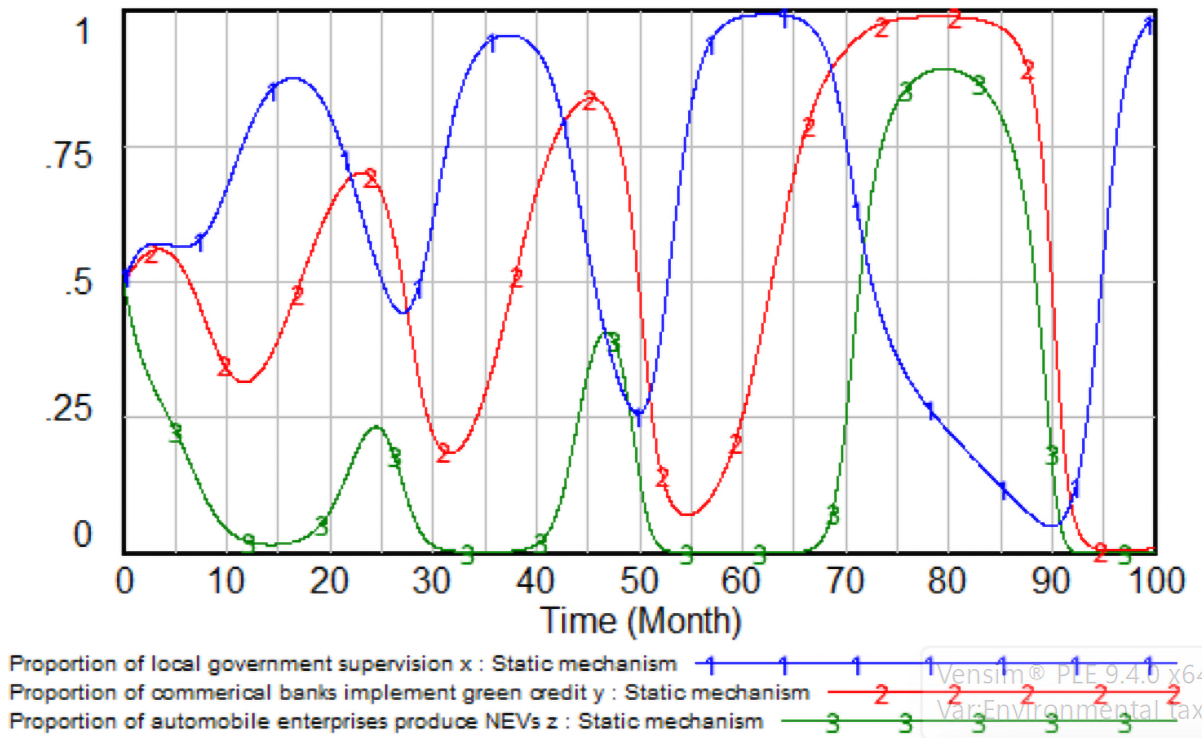

Fig. 6. Evolutionary trajectory in static reward and punishment mechanism.

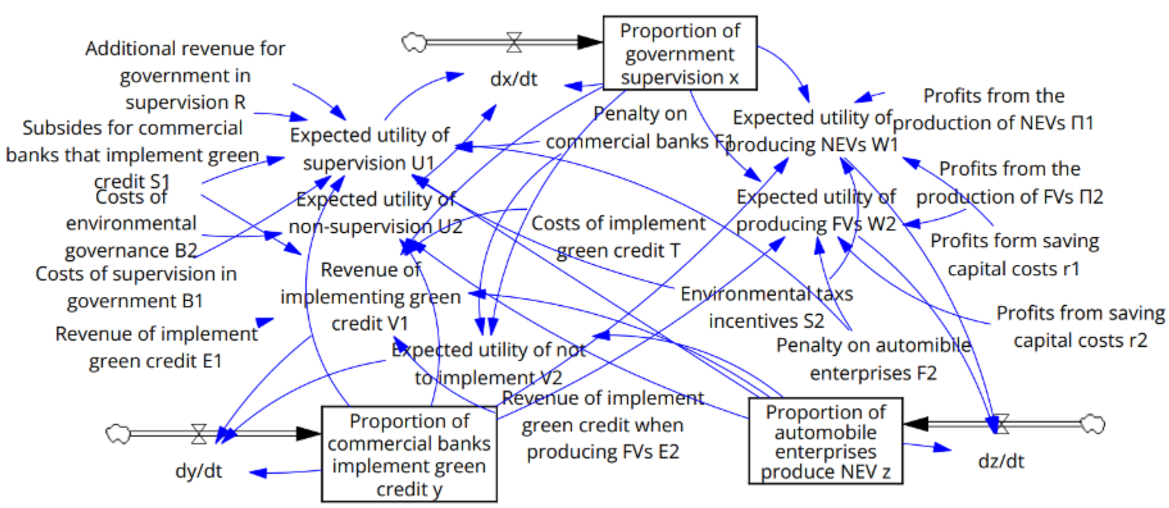

Fig. 7. Three-party game system dynamics model.

commercial banks and automobile companies are inversely proportional to the probability that they choose to implement green credit and produce NEVs.

Accordingly, the replication dynamic equations under dynamic reward and punishment mechanisms are constructed as follows:

$$f(x)=\frac{\mathrm{d}x}{\mathrm{d}t}=x(1-x)\{y[-(1-y)s_1]+ z[R-(1-z)s_2+(1-y)f_1-(1-z)f_2]+ yz[-(1-y)f_1]-B_1+(1-z)f_2\}, \tag{31}$$

$$f(y)=\frac{\mathrm{d}y}{\mathrm{d}t}= y(1-y)[x(1-y)s_1+xz(1-y)f_1+z(E_1-E_2)+E_2-T], \tag{32}$$

$$f(z)=\frac{\mathrm{d}z}{\mathrm{d}t}=z(1-z)[x(1-z)(s_2+f_2)+y(r_1-r_2)+\pi_1-\pi_2]. \tag{33}$$

Let $f(x)=0,\ f(y)=0,\ f(z)=0$, the eight pure-strategy equilibrium points can be obtained. When

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$$0 < \frac{T - E_2 - z(E_1 - E_2)}{z(1-y)f_1 + (1-y)s_1} < 1,$$

$$0 < \frac{\pi_2 - \pi_1 - x(1-z)(s_2 + f_2)}{r_1 - r_2} < 1,$$

$$0 < \frac{B_1 - (1-z)f_2 - y(1-y)(-s_1)}{(1-y)^2 f_1 + R - (1-z)s_2 - (1-z)f_2} < 1.$$

There is another equilibrium point (x', y', z') in the system. In meeting

$$0 < T - E_2 - z(E_1 - E_2) < z(1-y)f_1 + (1-y)s_1,$$

$$0 < \pi_2 - \pi_1 - x(1-z)(s_2 + f_2) < r_1 - r_2,$$

$$(1-z)f_2 < B_1 - y(1-y)(-s_1) < (1-y)(1-y)f_1 + R - (1-z)s_2,$$

let

$$R = 3,\ B_1 = 0.2,\ E_1 = 7,\ E_2 = 6.1,$$
$$\pi_1 = 5.3,\ \pi_2 = 7.8,\ r_1 = 2.313,\ r_2 = 0.27,$$
$$s_1 = 3,\ s_2 = 3.2,\ f_1 = 0.75,\ f_2 = 1.16,\ T = 7.5.$$

Then, ten solutions are listed below: (0, 0, 0), (0, 0, 1), (0, 1, 0), (0, 1, 1), (1, 0, 0), (1, 0, 1), (0, 1, 1), (1, 1, 1), (0.5957, 0.4792, 0.4144), (0.5579, 0.3499, 0.2662).

The Jacobin matrix of the system is:

$$J(f(x,y,z)) = \begin{bmatrix} \frac{\partial f(x)}{\partial x} & \frac{\partial f(x)}{\partial y} & \frac{\partial f(x)}{\partial z} \\ \frac{\partial f(y)}{\partial x} & \frac{\partial f(y)}{\partial y} & \frac{\partial f(y)}{\partial z} \\ \frac{\partial f(z)}{\partial x} & \frac{\partial f(z)}{\partial y} & \frac{\partial f(z)}{\partial z} \end{bmatrix}. \quad (34)$$

Notes:

$$\frac{\partial f(x)}{\partial x} = (1-2x) - \{3y(1-y) + z[3 + 0.75(1-y)(1-y) - 4.36(1-z)] - 0.2 + 1.16(1-z)\},$$

$$\frac{\partial f(x)}{\partial y} = x(1-x)[-3(1-2y) - 1.5z(1-y)],$$

$$\frac{\partial f(x)}{\partial z} = x(1-x)(-1.77 + 8.72z - 1.5y + 0.75y^2),$$

$$\frac{\partial f(y)}{\partial x} = y(1-y)(3 + 0.75z)(1-y),$$

$$\frac{\partial f(y)}{\partial y} = (1-2y)[(3x + 0.75xz)(1-y) + 0.9z - 1.4] + y(1-y)x(-3 - 0.75z),$$

$$\frac{\partial f(y)}{\partial z} = y(1-y)[0.75x(1-y) + 0.9],$$

$$\frac{\partial f(z)}{\partial x} = 4.36z(1-z)(1-z),$$

$$\frac{\partial f(z)}{\partial y} = 2.043z(1-z),$$

$$\frac{\partial f(z)}{\partial z} = (1-2z)[4.36x(1-z) + 2.043y - 2.5] - 4.36xz(1-z).$$

By analyzing the Jacobi matrix $J(f(x,y,z))$, expect (0.5579, 0.3550, 0.2662), all the other solutions have eigenvalues greater than zero, so they are not stable solutions. We substitute (0.5579, 0.3550, 0.2662) into the Jacobi matrix $J(f(x,y,z))$ and obtain:

$$J(f(x,y,z)) = \begin{bmatrix} 0.0000 & -0.2860 & 0.0291 \\ 0.4731 & -0.4601 & 0.2666 \\ 0.6250 & 0.3991 & -0.4752 \end{bmatrix}. \quad (35)$$

We calculate that the eigenvalues $(\lambda_1, \lambda_2, \lambda_3) = (-0.0493 + 0.3523i, -0.0493 - 0.3523i, -0.7828 + 0.0000i)$. As all eigenvalues are negative, (0.5579, 0.3550, 0.2662) is the ESS.The simulation result is shown in Fig. 8.

As shown in Fig. 8, when compared to the static reward and punishment mechanism, the system gradually tends to a stable value from a slight fluctuation at the beginning and

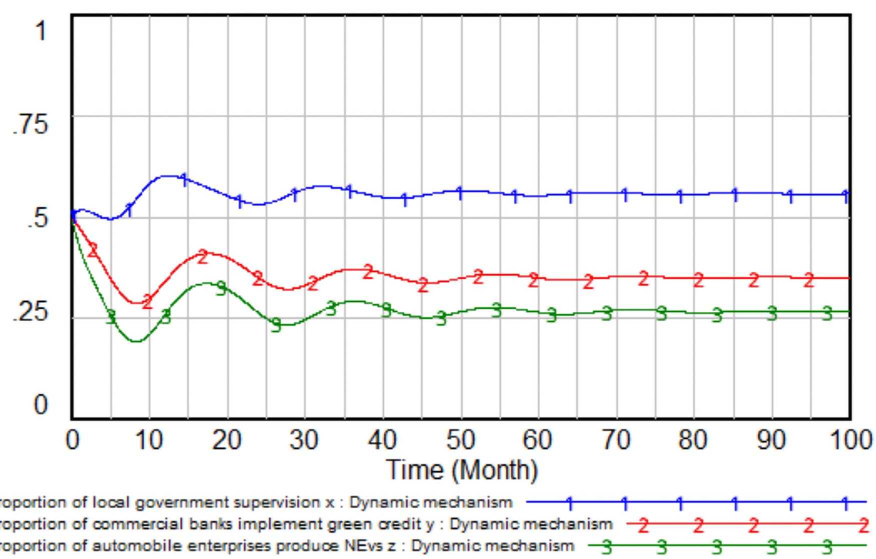

Fig. 8. Evolutionary trajectory in dynamic reward and punishment mechanism.

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eventually reaches a stable state, indicating that the incorporation of dynamic reward and punishment is effective for the improvement of the system, and it is also more in line with the actual situation. To promote commercial banks to help the green development of automobile enterprises, the government should be flexible in the measures it takes in accordance with the subject behavior strategy.

5.2.2 Simulation analysis of initial probability change

Let $R = 3$, $B_1 = 0.2$, $E_1 = 7$, $E_2 = 6.1$, $\pi_1 = 5.3$, $\pi_2 = 7.8$, $r_1 = 2.313$, $r_2 = 0.27$, $s_1 = 3$, $s_2 = 3.2$, $f_1 = 0.75$, $f_2 = 1.16$, $T = 7.5$, the initial probabilities of the three parties are adjusted to $x = 0.8$, $y = 0.8$, $z = 0.8$. Increasing the probability of the three parties' initial willingness to explore changes in their behavior. The simulation results are presented in Fig. 9.

As shown in Fig. 9, when the initial willingness of the three parties increases, the system rapidly converges from the initial state of slight fluctuation to a stable value with high probability, and the probability of the government choosing supervision tends to 1 over time. This indicates that in a real situation when the three parties actively assume their duties; for instance, the government actively assumes the duties of supervision and does a good job in macrocontrol work. According to the support and guidance of national policies, commercial banks actively implement green credit, and automobile enterprises actively invest in technical innovation funds and vigorously produce NEVs to promote their own green development. At this time, the system evolution will be more stable.

5.2.3 Simulation analysis of upper limit of reward and punishment

Let $R = 3$, $B_1 = 0.2$, $E_1 = 7$, $E_2 = 6.1$, $\pi_1 = 5.3$, $\pi_2 = 7.8$, $r_1 = 2.313$, $r_2 = 0.27$, $s_1 = 3.2$, $s_2 = 3.2$, $f_1 = 2$, $f_2 = 1.16$, $T = 7.5$, exploring how upper limit of reward and punishment affects the evolution results of commercial banks. The simulation results are presented in Fig. 10.

As shown in Fig. 10, when the government's reward and punishment for commercial banks increase, the probability of commercial banks implementing green credit increases, and over time, the evolution result converges from the initial fluctuating state to a higher probability stable value. This is because, when the reward ceiling increases, the revenues of commercial banks that choose to implement green credit increase, and commercial banks that choose not to implement green credit face higher punishments. Similar to for-profit organizations, commercial banks also change their strategic behavior as earnings change.

Let $R = 3$, $B_1 = 0.2$, $E_1 = 7$, $E_2 = 6.1$, $\pi_1 = 5.3$, $\pi_2 = 7.8$, $r_1 = 2.313$, $r_2 = 0.27$, $s_1 = 3$, $s_2 = 4$, $f_1 = 0.75$, $f_2 = 2.16$, $T = 7.5$, exploring how upper limit of rewards and punishments have affected the evolution of automobile enterprises. The simulation results are presented in Fig. 11.

As Fig. 11 shows, when the government's rewards and punishments for automobile enterprises increase, the evolution result converges from the initial fluctuating state to a higher stable value. This is because when the reward ceiling increases, the rewards for automobile enterprises that choose to produce NEVs will increase. Similarly, when the punishment ceiling increases, the punishments for the production of FVs will also increase, all of which have prompted automobile enterprises to actively carry out technical innovation and produce NEVs. Simultaneously, it can also be seen that the government, acting as a regulator, can adjust the equilibrium point between commercial banks and automobile companies by adjusting the ceiling of rewards and punishments and better conduct macrocontrol of the entire system.

5.2.4 Simulation analysis of r_1–r_2 difference value change

$r_1 - r_2$ represents the difference in profits between the production of NEVs and FVs when the automobile enterprise obtains green credit. Let $R = 3$, $B_1 = 0.2$, $E_1 = 7$, $E_2 = 6.1$, $\pi_1 = 5.3$, $\pi_2 = 7.8$, $r_1 = 3.313$, $r_2 = 0.27$, $s_1 = 3$, $s_2 = 3.2$, $f_1 = 0.75$, $f_2 = 1.16$, $T = 7.5$. The simulation results are presented in Fig. 12.

As shown in Fig. 12, when the $r_1 - r_2$ increases, the probability of automobile enterprises choosing to produce NEVs will

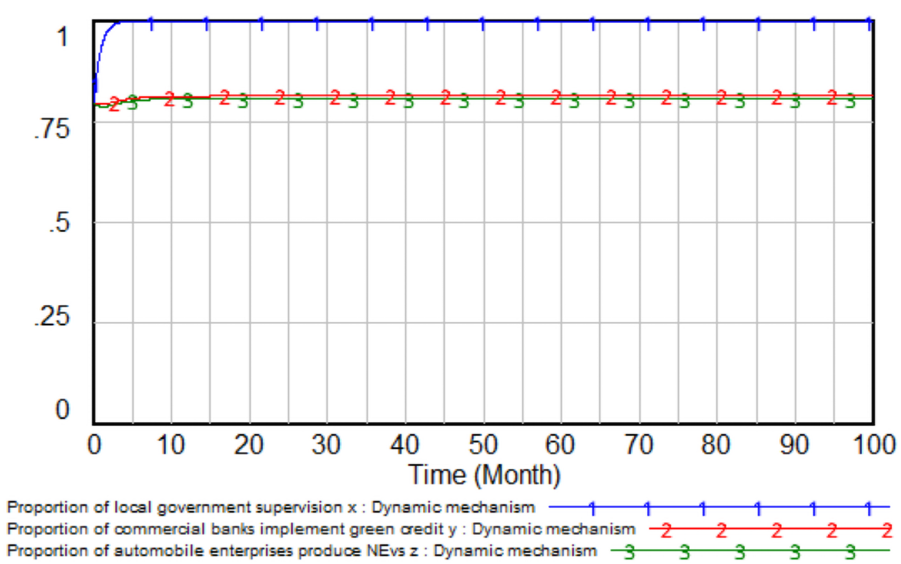

Fig. 9. Evolutionary trajectory of initial probability change in dynamic reward and punishment mechanism.

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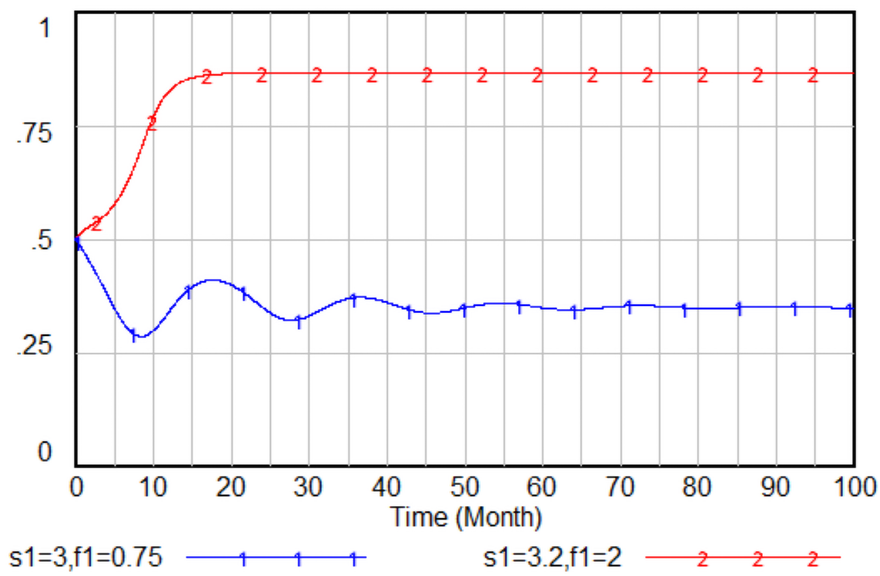

Fig. 10. Evolutionary trajectory of commercial banks with different s_1 and f_1.

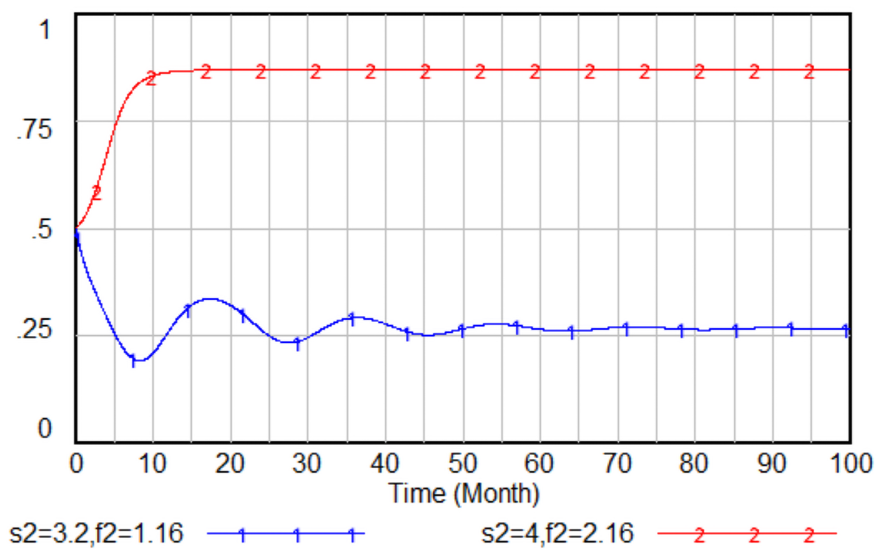

Fig. 11. Evolutionary trajectory of automobile enterprises with different s_2 and f_2.

increase and eventually converge to 1. This indicates that automobile enterprises can obtain higher profits by means of green credit to produce NEVs increases, their willingness to actively produce NEVs, which can effectively facilitate the green development of automobile enterprises.

6 Conclusions

Based on the assumption of bounded rationality and from the perspective of an evolutionary game, this study constructs a tripartite game model of the government, commercial banks, and automobile enterprises, and conducts an analysis and numerical simulation from the two aspects of static and dynamic reward and punishment mechanisms to explore the evolutionary paths of the three parties in different situations. The conclusions are as follows:

(Ⅰ) When the increase in intangible benefits, such as government credibility, is greater than the supervision costs, subsidies, and environmental tax incentives for commercial banks and automobile enterprises, the government chooses to supervise. When the sum of the actual benefits obtained from the implementation of green credit and the fines incurred when it is not implemented is > 0, commercial banks choose to implement green credit. Under government supervision, when the actual income obtained by automobile enterprises from the production of NEVs is greater than that from the production of FVs, automobile enterprises will not choose to produce FVs. At this point, the system reaches its ideal state (1, 1, 1). To achieve the ideal state of the system, the government can establish various regulatory channels to encourage all parties to actively participate in the supervision of the behavior of commercial banks and automobile enterprises, and reduce the costs of supervision. Simultaneously, reasonable

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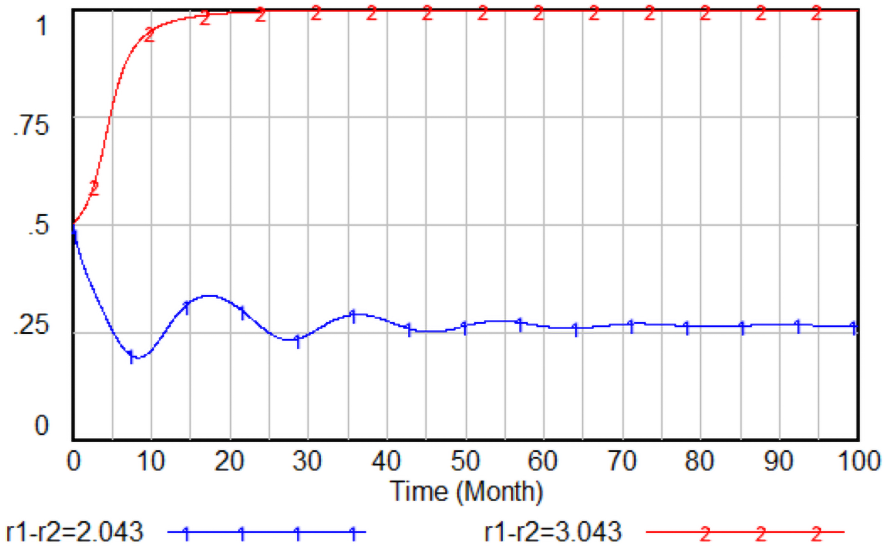

Fig. 12. Evolutionary trajectory of automobile enterprises with different $r_1 - r_2$.

reward and punishment mechanisms should be established to effectively mobilize the enthusiasm of commercial banks and automobile enterprises.

(Ⅱ) Under a static reward and punishment mechanism, the three parties must continuously learn and adjust their strategies to maximize their respective interests, resulting in a periodic fluctuation state of the evolutionary system that is unable to achieve stability. The government, acting as a regulator, can not effectively restrict the behavior of commercial banks and automobile enterprises and falls into a situation of weak supervision.

(Ⅲ) Introducing a dynamic reward and punishment mechanism effectively solves the system fluctuation problem and compensates for the deficiency of static rewards and punishments. As the evolutionary process progresses, the system gradually tends towards a stable state, which indicates that the dynamic reward and punishment mechanism effectively improves the system state and is closer to the real situation.

(Ⅳ) Under a dynamic reward and punishment mechanism, an increase in the tripartite initial intention probability can effectively promote the evolutionary stability of the system. The government can encourage commercial banks to implement green credit and automobile enterprises to produce NEVs by raising the ceiling for reward and punishment for commercial banks and automobile enterprises. When the difference between the profits obtained by automobile enterprises from the green credit of commercial banks to produce NEVs and FVs increases, automobile enterprises become more willing to produce NEVs, indicating that, with the help of commercial banks' green credit, automobile enterprises can better carry out green development.

There are some limitations in this paper. The real situation is more complex than the model. The stakeholders of automobile enterprises involve many subjects, so the four-party game model of government, commercial banks, enterprises, and the public can be established to further study the green development of automobile enterprises. In addition, this paper only considering the logical relationship between the parameter, and the actual data of some parameters is difficult to obtain, the accuracy of the model needs to be improved. Therefore, the next research direction is to obtain more real data through questionnaire surveys and consulting experts and scholars combined with professional statistical analysis data.

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Conflict of interest

The authors declare that they have no conflict of interest.

Biography

Yu Dong is a Vice President of Anhui University of Science and Technology and an Associate Professor at the University of Science and Technology of China (USTC). He received his Ph.D. degree in Management from the USTC. His research mainly focuses on decision science and operations management.

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