Evolutionary Game between Local Government and Enterprises under Penalty Mechanism of Carbon Emission Reduction

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Abstract

As the main source of carbon emissions, enterprises are a crucial factor in carbon emission reduction. The paper based on the evolutionary game model of carbon emission reduction between local governments and enterprises under the penalty mechanism, analysis the evolutionary stability strategy of local governments and enterprises under different scenarios, and MATLAB simulation is used to analyze the impact of government supervision costs, enterprise emission reduction costs and government penalties on the evolution path. The results of the study show that when the fines imposed by local governments on enterprises are smaller than the cost of government supervision, the government chooses "no supervision" and enterprises choose to "dishonestly" carbon emission reduction; when the fine imposed by local governments on enterprises is greater than the government supervision costs, but the emission reduction cost of enterprises is greater than the sum of fines and credit losses, and enterprise choose to be "honesty" carbon emission reduction cost is too large, the government chooses "regulation" and companies choose "dishonesty".

Keywords: *evolutionary game; analogue simulation; carbon emission reduction*

1.Introduction

With the development of the economy, China has become the largest carbon emitting country, facing huge carbon emission pressure[1], green and low-carbon development has become one of China's important strategic initiatives, such as in the 14th Five-Year Plan, there are 4 chapters that talk about green and low-carbon related issues. In 2021, the report of China's two sessions (NPC and CPPCC) clearly defined the goal of "striving to peak carbon dioxide emissions by 2030 and striving to achieve carbon neutrality by 2060". Therefore, carbon emission reduction is bound to be the first problem in China's future development. As the main source of carbon emissions, enterprises are a crucial influencing factor in carbon emission reduction[2], and due to the existence of carbon emission reduction costs, enterprises are driven by profit maximization in carbon emission reduction may have speculative behavior, requiring government supervision and regulation.

In recent years, evolutionary game theory has become a popular way to research on carbon emission reduction strategies, such as Zhao LR et al. [3]based on the perspective of enterprises, build the evolutionary game model of enterprise carbon emission reduction behavior to studied the strategic choices of enterprise emission reduction behavior in carbon emission trading. Fu QF et al.[4]analyzes the strategic choices of upstream and downstream enterprises in the supply chain for investment in carbon emission reduction. Lu JC et al.[5]based on the perspective of government and enterprise, studied the evolution stability strategies of government and enterprise in the initial allocation of carbon emission rights. Wang WJ et al.[6]analyzes the impact of carbon tax rates and various elements of the game on strategy choices by constructing an evolutionary game model of local governments and enterprises under the carbon tax mechanism. The paper based on evolutionary game theory and carbon emission reduction penalty mechanism, studies the choice of carbon emission reduction evolution strategies of government and enterprises under different scenarios, and uses MATLAB to simulate the stable path of government and enterprise carbon emission reduction evolution, and find out the key influencing factors. Through research, it

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provides some reference for the future research on the carbon emission reduction strategy of enterprises

2. Evolutionary game model construction and stability analysis

2.1. Research hypothesis and model construction

The game objects of this paper are local government and enterprise that need to carry out carbon emission reduction, and the strategic choices of those are: supervision and non-supervision; honesty and dishonesty (honesty refers to the fact that enterprise truthfully invest in carbon emission reduction costs, including carbon emission reduction technology investment and the trading of carbon trading rights as the enterprise strictly abides by the policy of carbon emission reduction; dishonesty refers to the fact that enterprise driven by interests, cannot truthfully report their carbon emissions, and do not purchase additional carbon emissions for emissions exceeding carbon quotas.）

In order to better analyze the long-term game state between local government and enterprise, there are the following assumptions:

Hypothesis 1: The main part of implementation of China's carbon emission reduction policy can be divided into three levels: central government, local government and enterprise[2].The relationship between the three is reflected in the central government initiating and promulgating guiding policies on carbon emission reduction, and then the local government implements the policy and implements it on enterprises, so there is a "delegate-execute" relationship between the central government and the local government, which leads to possible inconsistencies in the interests between the two. Due to the paper mainly studies the evolutionary game between local governments and enterprise, so only the situation of consistency of interests between the central and local governments is considered, and the situation of inconsistent interests between the two needs to be studied separately[7].

Hypothesis 2: According to the carbon reduction policy, local governments will initially allocate a certain amount of carbon allowances to enterprise（assuming Q）, and the emissions of enterprise when there are no carbon emission reduction requirements is D, so it can be concluded that the carbon reduction target of enterprises is $\Delta Q = Q - D$. At this time, the actual carbon reduction amount of the enterprise after the emission reduction investment is ΔQ_1, when $\Delta Q - \Delta Q_1 > 0$, the enterprise needs to purchase a certain amount of carbon emission rights.

Hypothesis 3: Assuming the basic benefit of local governments is I, and when enterprise choose to reduce carbon emissions honestly, they will bring additional environmental benefits (assuming E).

Hypothesis 4: Assuming the benefits for enterprise to choose honest carbon emission reduction is H, and ΔH means the additional benefit of enterprise, when the government doesn't regulate, and the enterprise choose dishonest carbon emission reduction.

Hypothesis 5: When local governments choose supervision, assuming the cost of that is C_1, and when enterprise choose to dishonest carbon emission reduction, the cost of that is C_2, and if enterprise choose to honest carbon emission reduction, assuming the additional cost is P(it including carbon emission reduction technology investment and buy carbon trading rights).

Hypothesis 6: When the government finds that the enterprise has dishonesty of carbon emissions reduction with the supervision, it will charge a penalty for the dishonest behavior of the enterprise (assuming M), and the enterprise will also bear some credit loss fees for its dishonest behavior (assuming L).

Hypothesis 7: Assuming the proportion of local governments choose the "supervision" strategy is x , and the proportion of the "non-supervision" strategy is $1 - x$; the proportion of enterprise choose the "honest" strategy is y, and the proportion of "dishonest" strategy is $1 - y$. The income matrix of local governments and enterprises is shown in Table 1.

Table 1. Benefit matrix of local government and enterprise strategic space

Government/Business	Honesty (*y*).	Dishonesty (*1-y*).
Regulation (*x*).	$I + E - C_1$; $H - C_2 - P$	$I - C_1 + M$; $H - C_2 - M - L$
Not regulated (*1-x*).	$I + E$; $H - C_2 - P$	I ; $H - C_2 + \Delta H$

2.2. Evolutionary game stability analysis

For local governments, the expected benefits of choose "supervision" strategy are:

$$G_1 = y(I + E - C_1) + (1 - y)(I - C_1 + M) \quad (1)$$

The expected benefit of choose "non-supervised" strategy is:

$$G_2 = y(I + E) + (1 - y)I \quad (2)$$

It can be seen that the average income of local governments is:

$$G = xG_1 + (1 - x)G_2 \quad (3)$$

The replication of dynamic equation when local government choose "supervision" strategy is:

$$G(x) = \frac{dx}{dt} = x(G_1 - G) = x(1 - x)(M - C_1 - yM) \quad (4)$$

For enterprise, the expected benefits of choose "honesty" strategy are:

$$E_1 = x(H - C_2 - P) + (1 - x)(H - C_2 - P) \quad (5)$$

The expected benefits of choose "dishonesty" strategy is:

$$E_2 = x(H - C_2 - M - L) + (1 - x)(H - C_2 + \Delta H) \quad (6)$$

It can be seen that the average income of enterprise is:

$$E = yE_1 + (1 - y)(E_2) \quad (7)$$

The replication of dynamic equation when enterprise chooses "honesty" strategy is:

$$E(y) = \frac{dy}{dt} = y(1 - y)[x(M + L + \Delta H) - \Delta H - P] \quad (8)$$

According to equation (4) and (8), the derivative of $G(x)$ is $G'(x) = (1 - 2x)(M - C_1 - yM)$, and the derivative of $E(y)$ is $E'(y) = (1 - 2y)[x(M + L + \Delta H) - \Delta H - P]$. According to the theorem of differential equations and the nature of evolutionary stabilization strategies, when $G(x^*) = 0$ and $G'(x^*) < 0$, in the phase diagram of the copied dynamic equation, x^* displayed as a point that intersects the horizontal axis and has a negative tangent slope at the intersection, and that is the evolutionary stability strategy of the corresponding game replication dynamic[8]. In the same way, the evolutionary stabilization strategy of $E(y)$ can be obtained.

Then, according to the nature of the evolutionary game, equation (4) and (8) can constitute the dynamic replication system about local government and enterprise under the carbon emission reduction penalty mechanism, and through the above stable evolution strategy analysis, it can be seen that the system has five equilibrium points: (0, 0),(0, 1),(1, 0),(1, 1),($\frac{\Delta H+P}{M+L+\Delta H}$, $\frac{M-C_1}{M}$). After that, take the study of the evolutionary stabilization strategy of the dynamic replication system. According to the method proposed by Friedman[9], the stability of the equilibrium point of the system can be obtained by using the system's Jacobian matrix analysis. The Jacobian matrix of the system is as follows:

$$J = \begin{bmatrix} \partial x^*/\partial x & \partial x^*/\partial y \\ \partial y^*/\partial x & \partial x^*/\partial y \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$
$$= \begin{bmatrix} (1 - 2x)(M - C_1 - yM) & Mx(x - 1) \\ y(1 - y)(M + L + \Delta H) & (1 - 2y)[x(M + L + \Delta H) - \Delta H - P] \end{bmatrix}$$

And $tr(J) = a_{11} + a_{22} = (1 - 2x)(M - C_1 - yM) + (1 - 2y)[x(M + L + \Delta H) - \Delta H - P] det(J) = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix}$.

Take five equilibrium points into the Jacobi matrix and concretely analysis, the results are shown in Table 2. According to the nature of the evolutionary game, when$tr(J) < 0$ and $det(J) > 0$, the equilibrium point of the replication dynamic equation is stable and is an evolutionary stability strategy(ESS).

Table 2. Stability analysis results

Equilibrium point	$tr(J)$	$det(J)$	Variable analysis	Local stability
(0 · 0)	$M - C_1 - \Delta H - P$	$(C_1 - M)(\Delta H + P)$	when $M > C_1$, $det(J) <$ 0, $tr(J)$is uncertain	Saddle point
			When $M < C_1, det(J) >$ 0, $tr(J) < 0$	ESS
(0 · 1)	$\Delta H + P - C_1$	$-C_1(\Delta H + P)$	$det(J) < 0$, when $\Delta H + P > C_1, tr(J) > 0$	Saddle point
			$det(J) < 0$, when $\Delta H + P < C_1 tr(J) > 0$	Saddle point
(1 · 0)	$C_1 + L - P$	$(C_1 - M)(M + L - P)$	when $M < C_1$ and $P < M + L, det(J) > 0, tr(J) > 0$	Saddle point
			when $M < C_1$ and $P > M + L, det(J) < 0, tr(J)$is uncertain	Saddle point
			when $M > C_1, P < M + L$, $det(J) <$ 0, $tr(J)$is uncertain	Saddle point
			when $M > C_1$ and $P > M + L, det(J) > 0, tr(J) < 0$	ESS
(1 · 1)	$C_1 + P - M - L$	$-C_1(M + L - P)$	when $P > M + L, det(J) > 0, tr(J) > 0$	Saddle point
			when $P < M + L$, $det(J) < 0, tr(J)$ is uncertain	Saddle point
$(\frac{\Delta H + P}{M + L + \Delta H}$	0	$\frac{C_1(\Delta H + P)(}{M(M + L}$	$tr(J) = 0$	Saddle point

3.Simulation and result analysis of evolutionary stabilization strategy

In order to further analyze the impact of supervision costs, carbon emission reduction costs and government fines on the strategy evolution of both sides of the game, the paper will use MATLAB tools to numerically simulate the evolution process of local government and enterprise.

3.1. Simulation and result analysis of strategy 1

When $M < C_1$, the evolutionary stabilization strategy was (0, 0), that means "non-supervision, dishonesty".

Combine equations (4) and equation (8), in order to meet the condition $M < C_1$, and also to simplify the analysis process, reference the previous research[6] and police on effluent charge, assuming $M = 1.5, C_1 = 2, L = 1, \Delta H = 1.8, P = 0.5$ (units are 100,000 yuan), and set the initial decision probability is (0.5, 0.5). Enter the above variables into the simulation, and then obtain the evolution path of the evolution stability strategy, as shown in Figure 1.

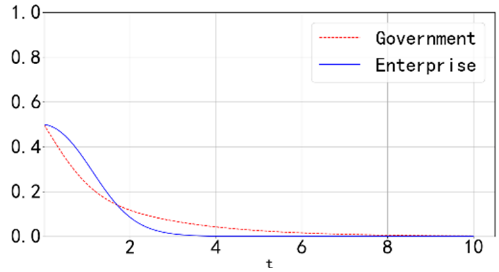

Figure 1. Simulation result of $M = 1.5, C_1 = 2$

It can be seen from Figure 1, that when $M < C_1$, the simulation results and the above replication of the dynamic equation analysis results are basically the same, the evolutionary stability policy is (0, 0), that means "non-supervision, dishonesty". And according to the evolution path in the figure, it can be seen that when $t < 1.8$, the government evolves faster, and when $t > 1.8$, the enterprise evolves faster. This shows that at the beginning, due to factors such as government supervision, enterprise didn't generally choose the "dishonesty" strategy. But later with the decline of government supervision, and as continuous imitation and learning, the number of enterprises that chose "honesty" emission reduction fell sharply, and finally reached the evolutionary stability strategy.

The paper uses the control variable method to further analyze the impact of government supervision costs M and government fines C_1 on the evolution path. At first, it is assumed that numerical value of other variables are unchanged, simulated the evolution path when $C_1 = 3$, and make the analysis and comparison, and the results are shown in Figure 2: When C_1 is enlarged, the evolution speed of the government and enterprises is also increasing, and the growth scope of the government is greater than the growth scope of the enterprise, and under this condition, the evolution speed of the government has always been greater than the evolution speed of the enterprise. This suggests that when the government supervision costs grow large enough, the government's strategic choices will not be affected by enterprises. And whether or not enterprises generally choose "dishonest", the government will always choose "non-supervision". (In figure2, $M = 1.5, C_1 = 3, L = 1, \Delta H = 1.8, P = 0.5$(units are 100,000 yuan))

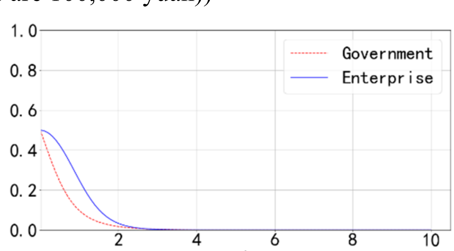

Figure 2. Simulation result of $M = 1.5, C_1 = 3$

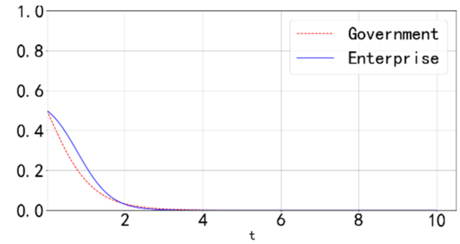

Figure 3. Simulation result of $M = 0.5, C_1 = 2$

Secondly, change the numerical value of M and don't change other variables, simulated the evolution path when $M = 0.5$, the results shown in Figure 3: when M is reduced, the evolution speed of the government and the enterprise is increasing, and the evolution speed of the government is greater than the the enterprise. This suggests that when the fine is reduced, the time of government to reach the evolutionary stability strategy is greatly shortened, and its choice is not affected by the enterprise. (In figure3, $M = 0.5, C_1 = 2, L = 1, \Delta H = 1.8, P = 0.5$(units are 100,000 yuan))

3.2. Simulation and result analysis of strategy 2

When $M > C_1$ and $P > M + L$, the evolutionary stability strategy was (1， 0), that means "supervision, dishonesty".

Combine the replication dynamic equations of equations (4) and (8), and also to meet the condition $M > C_1, P > M + L$, assuming $M = 1.5, C_1 = 0.5, L = 1, \Delta H = 1.8, P = 3$(units are 100,000 yuan), and set the initial decision probability to (0.5, 0.5). Enter the above variables into the simulation, and then obtain the evolution path of the evolution stability strategy, as shown in Figure 4.

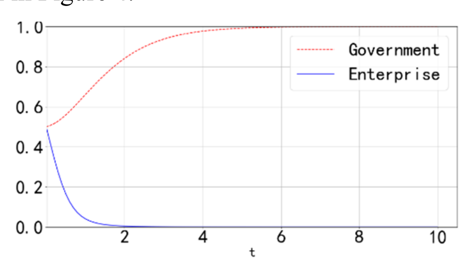

Figure 4. Simulation result of $\mathrm{M} = 1.5, \mathrm{P} = 3$

It can be seen from Figure 4, when $M > C_1, P > M + L$, the simulation results and the above replication of the dynamic equation analysis results are basically the same, the evolutionary stability policy is (1, 0), that means "supervision, dishonesty". And according to the evolution path in the figure 4, it can be seen that the evolution speed of enterprises is faster than the government, and the time for enterprises to reach the evolution stability strategy is shorter than the government. This shows that in the beginning, due to factors such as the supervision costs, the government did not immediately choose the "supervision" strategy, but later with the increase in the "dishonest" carbon emission reduction behavior of enterprises, the government chose the "supervision" strategy after a long period of evolution to reduce losses that caused by the failure of enterprises to be honest carbon emission reduction, and finally reached the evolutionary stability strategy.

As can be seen from the above, other variables are unchanged, and only change the government's fine M or the additional cost for carbon reduction P, and study the impact of those variables on the evolutionary path. When the other variables don't change and $P = 3.5$, the evolution path is obtained, and the result is shown in Figure 5: when P increases, the evolution speed of enterprises also increases, but the evolution speed of government does not change significantly. This shows that when the cost of emission reduction of enterprises continues to increase, the choice of "honesty" carbon emission reduction will cause enterprises to suffer losses, so from the long-term development of enterprises, enterprises will choose "dishonesty" and the choice of the government at this time will not be affected by enterprises, and no matter how fast the evolution of enterprises, the government will choose "supervision". (In figure5, $M = 1.5, C_1 = 0.5, L = 1, \Delta H = 1.8, P = 3.5$(units are 100,000 yuan))

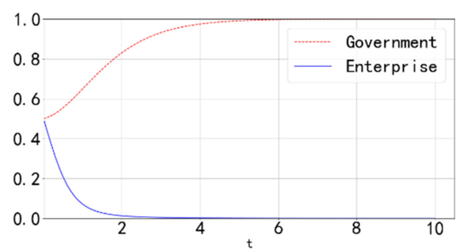

Figure 5. Simulation result of $M = 1.5, P = 3.5$

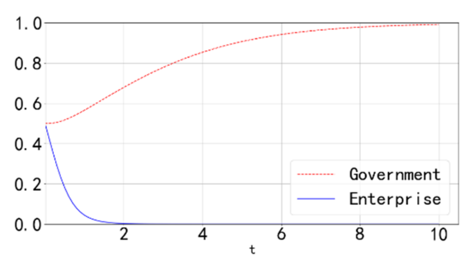

Figure 6. Simulation result of $M = 1, P = 3$

Then change the numerical value of M and don't change other variables, simulated the evolution path when $M = 1$, and the analysis results are shown in Figure 6: When M decreases, the evolution speed of enterprises is increases, while the evolution speed of government is decreases. This suggests that when the government's fines are declines, government deterrence against businesses has reduced. And with the cost of emission reduction unchanged, enterprises choose the "dishonesty" strategy to expect more revenue, and the government also reduces the supervision of enterprises due to the reduction of fines. (In figure6, $M = 1, C_1 = 0.5, L = 1, \Delta H = 1.8, P = 3$(units are 100,000 yuan))

4. Conclusions

In the paper, through the evolutionary game model, study the evolution path and equilibrium point of governments and enterprises under the carbon emission reduction penalty mechanism, there are two evolutionary stabilization strategies (*ESS*) in the replication dynamic system: strategy 1: When $M < C_1$, there is an evolutionary stabilization strategy (0，0), that means the government chooses "no supervision" and the enterprise chooses "dishonesty"; strategy 2: When $M > C_1$ and $P > M + L$, there is an evolutionary stability strategy (1，0), that means the government chooses" supervision", and enterprise chooses "dishonesty". And government fines on enterprises, government supervision costs, and carbon emission reduction costs of enterprises are key factors on the evolution path, those factors affecting the choice of government or enterprises.

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