The Evolutionary Game Study on Emission Reduction Strategies of Non-compliant Port and Shipping Enterprises under Media Participation and Government Supervision

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Abstract. With the development of science, technology, and the economy, China has become the world's largest emitter of carbon emissions. To achieve sustainable development in both the economy and the environment, promoting a low-carbon economy and implementing energy conservation and emission reduction measures are crucial. This study incorporates media participation as an effective source of government supervision into an evolutionary game model that addresses the choices of environmental regulations and emission reduction strategies for non-compliant port and shipping enterprises. Through the derivation and analysis of replicator dynamics equations and evolutionary stability, four different scenarios are identified, representing the strategic choices of government environmental regulations and non-compliant enterprise behaviors. Numerical simulations are used to demonstrate the evolutionary outcomes and pathways under different initial values and conditions. Additionally, the impact of media exposure probability on the strategic choices of the government and non-compliant enterprises is analyzed. The results indicate that a higher media exposure probability can promote non-compliant enterprises to opt for self-disclosure while reducing government regulatory costs. The government can enhance the positive involvement of the media to lower the regulatory costs imposed on non-compliant port and shipping enterprises, thereby improving the design of environmental regulations and achieving a win-win situation for economic and environmental performance.

1.Introduction

Currently, China has surpassed the United States to become the world's largest emitter of carbon dioxide[1]. Therefore, developing a low-carbon economy is urgent in order to achieve social and economic progress while ensuring sustainable development of the environment. As the largest developing country in the world, China has already achieved a 48% reduction in CO2 emissions per unit of GDP compared to 2005, surpassing its commitment to a 40-45% reduction by 2020 and achieving GDP growth of over four times. Additionally, China's "14th Five-Year Plan" sets the national strategic goal of peaking carbon emissions before 2030 and achieving carbon neutrality by 2060[2].

Therefore, in the issue of carbon emissions reduction, ideally, from the government's perspective, it should actively regulate the implementation of carbon reduction policies, while from the perspective of businesses, they should actively respond to the government's carbon reduction policies. However, in reality, both sides will take measures and react according to their own interests, which greatly influences the improvement of carbon emissions reduction, depending on the outcome of the game between the two parties[3]. Therefore, in-depth research on the evolutionary game between government regulatory agencies and businesses in low-carbon emissions reduction behavior is of significant importance to promote businesses in choosing reasonable production methods to achieve emission reduction goals, and to achieve mutual benefits in ecological environment and socio-economic development.

Regarding the issue of carbon emissions reduction, domestic and foreign scholars have extensively explored the strategic choices of emission reduction behavior, the calculation of carbon emission efficiency, and the main factors influencing carbon emission behavior. Currently, in addressing the systematic issue of government low-carbon policy formulation and business low-carbon emission reduction behavior, scholars have conducted research from the following perspectives: 1) Government and businesses: Li Jiali et al. explored the impact of government incentives on power generation companies adopting renewable energy generation[4]; Cheng Faxin et al. studied the optimal strategies for voluntary carbon reduction by enterprises under government subsidies[5]; Li Yuan et al. considered factors such as product carbon intensity, consumer low-carbon preferences, and carbon tax rates. By constructing a three-stage game model between the government and businesses, they provided technical guidance and data support for strategic decision-making in low-carbon supply chain management by the government and

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manufacturers[6]; 2) Third parties and relevant stakeholders: Zhang Kaize et al. emphasized the importance of incorporating third parties into environmental governance[7]; Zhang Lixin et al. used the third-party monitoring system of the European Union and the California carbon market to put forward policy recommendations for improving China's third-party supervision of the carbon market[8].

Existing literature provides a theoretical basis for research in the field of carbon emissions reduction, but there are still some limitations. Firstly, although previous studies have analyzed the rational and multi-agent evolutionary game, there is a lack of research on the role of third-party forces such as consumers and media in regulatory governance[9]. The existing literature provides important theoretical basis for exploring the relationship between government regulation and corporate emission reduction behavior under media exposure in this study, but when discussing government strategy choices, most existing studies simplify it as either regulation or non-regulation. As a matter of fact, the government can choose between active regulation and passive regulation, and there is a success rate of regulation under passive government supervision, as companies may disguise their actions to avoid fines.

Additionally, most existing literature focuses on the game between the media and businesses, but in terms of emission reduction, the goals of the media and the government should be aligned. With the continuous improvement of public environmental awareness, the media can participate in the implementation of government environmental regulations by exposing companies' violations. This makes the media an effective source of government supervision. Some companies that exceed emissions standards may choose to conceal their violations, making it difficult to detect these violations with limited government regulatory resources. However, the broad coverage and sensitivity of media supervision can focus on companies with excessive carbon emissions, limiting their actions and reducing their pollutant emissions[10]. On the other hand, some companies, considering their own performance, government subsidies, and public reputation, may voluntarily disclose carbon information. The probability of this behavior is positively related to the level of government subsidies and weakly positively related to corporate performance[11].

Therefore, based on the above points, this paper constructs an asymmetric evolutionary game model of government-business emissions reduction in the port and shipping industry, considering media exposure and voluntary disclosure, based on bounded rationality of the game participants. This provides a theoretical basis for the formulation and implementation of government environmental regulations.

2.Problem description and assumptions

2.1. Problem description

Under the condition of non-information asymmetry, the evolutionary game system includes two bounded rational groups: the government and non-compliant port and shipping companies. Additionally, this study incorporates the media as an exogenous variable into the game.

Based on the assumption of bounded rationality, the government employs two regulatory strategies, namely passive regulation and active regulation, in regulating the carbon emissions of non-compliant port and shipping companies. After violating emission regulations, these companies have the option to either self-disclose or disguise their violations.

This study assumes that under the strategy of active regulation, the government will undoubtedly detect the non-compliant emissions by port and shipping companies, while passive regulation has a certain probability of detecting violations. In the case where companies choose to disguise their violations and are discovered by the government, they will face significant fines for their pollution emissions. If not detected by the government, they can evade fines. However, if non-compliant port and shipping companies self-disclose their violations before being discovered by the government, the fines imposed will be reduced, but these companies will need to invest in implementing carbon reduction strategies.

The motivation behind the choice of disguising violations for the port and shipping companies lies in the desire to escape high fines based on a sense of luck. Moreover, self-disclosure incurs additional costs for technological innovation, operational expenses, and management expenses in implementing carbon reduction strategies, and these costs do not generate immediate returns. Hence, these companies choose to disguise their violations. At the same time, some companies opt for self-disclosure to avoid high fines and only pay lower fines, as well as to establish a good corporate reputation and earn the trust of the government and the public.

In the present day, the role of the media as a third-party force in supervision, in addition to the government and companies, is becoming increasingly significant. The monitoring results by the media are transparent and influential. This study considers media exposure as an exogenous variable and incorporates the probability of media exposure as a key parameter in the model.

2.2.Model Construction and Assumptions of Parameters

According to the assumption, regardless of the government's monitoring efforts, the probability of media exposure is $\alpha(0 < \alpha < 1)$, and it is independent of the success probability of passive regulation by the government.

Under the active regulatory strategy, the government incurs a monitoring cost of C_1, ensuring timely detection of violations by port and shipping companies. Under the passive regulatory strategy, the government incurs a monitoring cost of $\lambda C_1(0 < \lambda < 1)$, and the success probability of passive regulation is λ.

Under the government's environmental regulatory policy, there are two strategic choices for non-compliant port and shipping companies: self-disclosure and disguise. When a non-compliant company chooses to self-disclose its violations, it is required to pay a corresponding fine, B, to the government due to the disclosure of its violation. At the same time, the company gains reputation, W, as well as public support and recognition for implementing carbon reduction policies. Self-disclosing companies may also incur additional costs, R, for implementing carbon reduction measures such as shore power or LNG energy sources.

When a non-compliant port and shipping company chooses to disguise and conceal its violations, the local government bears the cost, C_0, of mitigating the pollution caused by the company. If the government's regulatory efforts are successful in detecting the violations, the non-compliant company is required to pay a fine for the emissions, F. The company also incurs losses, T, representing the damage to its reputation and the public's boycott of its services due to the violation[12]. However, if the government's regulatory efforts fail, the non-compliant company can evade the fine, as well as the losses in reputation and public boycott.

Considering the possibility of media exposure, with a probability of $\alpha(0 < \alpha < 1)$, if a non-compliant port and shipping company is exposed by the media, it will also be required to pay the fine, F. Furthermore, if the government's regulatory efforts fail, the government incurs a loss, D, representing the loss of government credibility. After media exposure, all reputation-related gains or losses for both the government and the non-compliant port and shipping company are multiplied by an amplification factor, β, where $\beta > 1$.

The parameters and their explanations, as shown in Table 1, are as follows:

Table 1. Parameters Assumptions and Explanations for the Payoffs of Both Players in the Game

Parameters	Descriptions
α	Media exposure probability, it has a value between 0 and 1.
C_1	The government's active regulatory cost
λ	The probability of the government's success in passive regulation, it has a value between 0 and 1
D	Loss of government reputation due to the failure of passive regulation and subsequent media exposure
R	Additional costs incurred by self-disclosing companies for implementing carbon reduction measures such as shore power and LNG energy
B	Fine imposed by the government on self-disclosing companies
F	Fine imposed by the government on non-compliant companies when they are detected $(F > B)$
T	Loss incurred by the non-compliant company, representing damage to its reputation and public boycott due to the violations[12]
C_0	Fine imposed by the government on non-compliant companies that choose to disguise and conceal their violations
W	Reputation gained by the port and shipping company, as well as the public support for carbon reduction companies
β	Amplification factor applied to all reputation-related gains or losses for both the government and the non-compliant company after media exposure, $\beta > 1$

3.Evolutionary Game under Static Punishment Mechanism

This section assumes that the government imposes a fixed fine on port and shipping companies, which represents the evolutionary game process under a static punishment mechanism.

3.1.Payment matrix and dynamic equations

Based on the model construction and parameter assumptions mentioned above, we can obtain the payment matrix for the government and the non-compliant companies under the static punishment mechanism (where B and F are constants) without considering the variable of media, as shown in Table 2.

Table 2. The game payment matrix for government regulation and non-compliant port and shipping companies

		Non-compliant port and shipping companies	
		Self-disclosure $\boldsymbol{y}$	Disguise $\mathbf{1-y}$
Government	Active regulation $\boldsymbol{x}$	$-C_1 + B$, $\alpha\beta W + (1-\alpha)W - B - R$	$-C_1 + F - C_0$, $-\alpha\beta T - (1-\alpha)T - F$
	Passive regulation $\mathbf{1-x}$	$-\lambda C_1 + B$, $\alpha\beta W + (1-\alpha)W - B - R$	$-\lambda C_1 + \lambda F - C_0 - (\alpha - \alpha\lambda)\beta D$, $-\alpha\beta T - (\lambda - \alpha\lambda)T - (\lambda + \alpha - \alpha\lambda)F$

Assuming that among the government entities, x proportion $(0 \leq x \leq 1)$ chooses proactive regulatory strategy, then $(1-x)$ proportion of the government chooses passive regulation. Among the non-compliant port and shipping companies, y proportion $(0 \leq y \leq 1)$ chooses self-disclosure, while $(1-y)$ proportion of the non-compliant companies chooses camouflaging and concealing [13].

The expected payoff for the government choosing proactive regulation is U_{G1}, the expected payoff for the government choosing passive regulation is U_{G2}, and the average expected payoff for the government is U_G, which can be calculated as follows:

$$U_{G1} = y(-C_1 + B) + (1-y)(-C_1 + F - C_0) \quad (1)$$

$$U_{G2} = y(-\lambda C_1 + B) + (1-y)[-\lambda C_1 + \lambda F - C_0 - (\alpha - \alpha\lambda)\beta D] \quad (2)$$

$$U_G = xU_{G1} + (1-x)U_{G2} \quad (3)$$

The replicator dynamics equation for the government's selection of regulatory strategy is:

$$f(x) = \frac{dx}{dt} = x\left(U_{G1} - \overline{U_G}\right) = x(1-x)(U_{G1} - U_{G2}) \quad (4)$$

The expected payoff for non-compliant companies choosing self-disclosure is U_{E1}, the expected payoff for choosing camouflaging and concealing is U_{E2}, and the average expected payoff for the companies is U_E, which can be calculated as follows:

$$U_{E1} = \alpha\beta W + (1-\alpha)W - B - R \quad (5)$$

$$U_{E2} = (-\alpha\beta - \lambda + \alpha\lambda)T - (\lambda + \alpha - \alpha\lambda)F - x(1-\lambda)(1-\alpha)(T+F) \quad (6)$$

$$U_E = yU_{E1} + (1-y)U_{E2} \quad (7)$$

The replicator dynamics equation for the selection of strategy by non-compliant companies is:

$$f(y) = \frac{dy}{dt} = y\left(U_{E1} - \overline{U_E}\right) = y(1-y)(U_{E1} - U_{E2}) \quad (8)$$

Proposition 1. The equilibrium points of the above replicator dynamics system are (0, 0), (1, 0), (0, 1), (1, 1), and $(x_1^*,\ y_1^*)$, where $x_1^* \in [0,1]$ and $y_1^* \in [0,1]$.

$$x_1^* = \frac{-C_1 + F + \alpha\beta D}{F + \alpha\beta D}$$

$$y_1^* = \frac{-(\alpha\beta + 1 - \alpha)W + B + R + (-\alpha\beta - \lambda + \alpha\lambda)T - (\lambda + \alpha - \alpha\lambda)F}{(1-\lambda)(1-\alpha)(T+F)}$$

Proof 1. By solving $f(x) = 0$, we obtain $x_1 = 0, x_2 = 1$, and $y_3 = \frac{-C_1+F+\alpha\beta D}{F+\alpha\beta D}$ (denoted as y_1^* where $0 \leq y_1^* \leq 1$ holds). By solving $f(y) = 0$, we obtain $x_1 = 0, x_2 = 1$, and $y_3 = \frac{-C_1+F+\alpha\beta D}{F+\alpha\beta D}$ (denoted as x_1^* where $0 \leq x_1^* \leq 1$ holds). Therefore, we have four fixed equilibrium points (0, 0), (1, 0), (0, 1), (1, 1), and when $x_1^* \in [0,1]$, $y_1^* \in [0,1]$, we obtain the equilibrium point $(x_1^*,\ y_1^*)$.

3.2.Evolutionary stability analysis

According to equations (4) and (8), the Jacobian matrix[14] of the system is obtained as follows:

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

Where:

$$J_{11} = \frac{\partial f(x)}{\partial x} \quad (10)$$

$$J_{12} = \frac{\partial f(x)}{\partial y} \quad (11)$$

$$J_{21} = \frac{\partial f(y)}{\partial x} \quad (12)$$

$$J_{22} = \frac{\partial f(y)}{\partial y} \quad (13)$$

The determinant of matrix J is calculated using the formula $det\ \boldsymbol{J} = J_{11}J_{22} - J_{12}J_{21}$, and the trace of matrix J is calculated using the formula $tr\ \boldsymbol{J} = J_{11} + J_{22}$.

$$det\boldsymbol{J} = J_{11}J_{22} - J_{12}J_{21} \quad (14)$$

$$tr\,\boldsymbol{J} = J_{11} + J_{22} \quad (15)$$

Proposition 2.

- (0, 0) is an ESS of the replicator dynamic system when $C_1 - F > \alpha\beta D > 0$, $B + R > (\alpha\beta + 1 - \alpha)W + (\alpha\beta + \lambda - \alpha\lambda)T + (\lambda + \alpha - \alpha\lambda)F > 0$. The behavior strategy is (passive regulation, Disguise).
- (0, 1) is an ESS of the replicator dynamic system when $(\alpha\beta + 1 - \alpha)W + (\alpha\beta + \lambda - \alpha\lambda)T + (\lambda + \alpha - \alpha\lambda)F > B + R > 0$. The behavior strategy is (passive regulation, Self-disclosure).
- (1, 0) is an ESS of the replicator dynamic system when $\alpha\beta D > C_1 - F > 0$, $B + R > (\alpha\beta + 1 - \alpha)(W + T) + F > 0$. The behavior strategy is (active regulation, Disguise).
- (1, 0) is not an ESS of the replicator dynamic system even if $C_1 < 0, B + R > (\alpha\beta + 1 - \alpha)(W + T) + F > 0$.

Proof 2. The table below shows the expressions for the determinant and trace of the Jacobian matrix when the equilibrium points (0,0), (1,0), (0,1), (1,1), and (x_1^*, y_1^*) are substituted into it. Please note that the actual expressions for the determinant and trace of the Jacobian matrix will depend on the specific equations and parameters of the evolutionary game on the plane $M = \{(x,y) | 0 \leq x, y \leq 1\}$.

Table 3. The expressions for the Determinant and Trace of the Jacobian matrix for each equilibrium point

Equilibrium points	$\boldsymbol{det}$ & $\boldsymbol{tr}$	Expression Results
(0,0)	$det\boldsymbol{J}$	$(1-\lambda)(-C_1 + F + \alpha\beta D)$ $[(\alpha\beta + 1 - \alpha)W - B - R - (-\alpha\beta - \lambda + \alpha\lambda)T + (\lambda + \alpha - \alpha\lambda)F]$
	$tr\,\boldsymbol{J}$	$(1-\lambda)(-C_1 + F + \alpha\beta D) +$ $[(\alpha\beta + 1 - \alpha)W - B - R - (-\alpha\beta - \lambda + \alpha\lambda)T + (\lambda + \alpha - \alpha\lambda)F]$
(0,1)	$det\boldsymbol{J}$	$(1-\lambda)C_1$

		$[(\alpha\beta+1-\alpha)W-B-R-(-\alpha\beta-\lambda+\alpha\lambda)T+(\lambda+\alpha-\alpha\lambda)F]$
	$tr\,\boldsymbol{J}$	$-(1-\lambda)C_1-$ $[(\alpha\beta+1-\alpha)W-B-R-(-\alpha\beta-\lambda+\alpha\lambda)T+(\lambda+\alpha-\alpha\lambda)F]$
(1,0)	$det\,\boldsymbol{J}$	$-(1-\lambda)(-C_1+F+\alpha\beta D)$ $[(\alpha\beta+1-\alpha)(W+T)-B-R+F]$
	$tr\,\boldsymbol{J}$	$-(1-\lambda)(-C_1+F+\alpha\beta D)+$ $[(\alpha\beta+1-\alpha)(W+T)-B-R+F]$
(1,1)	$det\,\boldsymbol{J}$	$-(1-\lambda)C_1$ $[(\alpha\beta+1-\alpha)(W+T)-B-R+F]$
	$tr\,\boldsymbol{J}$	$(1-\lambda)C_1-$ $[(\alpha\beta+1-\alpha)(W+T)-B-R+F]$
(x_1^*,y_1^*)	$det\,\boldsymbol{J}$	$-x^*y^*(1-x^*)(1-y^*)(1-\lambda)^2(1-\alpha)(-F-\alpha\beta D)(T+F)$
	$tr\,\boldsymbol{J}$	0

Based on the expressions for the determinant and trace of the Jacobian matrix in Table 3, it can be concluded that there is no constant evolutionary stable strategy between the government and non-compliant port companies in this scenario. Both parties will choose different game strategies under different premises. Additionally, if the values of the conditions are near the critical values, even slight changes in the values can have a significant impact on the behavioral strategies chosen by the participants in the game. Next, let's analyze the different evolutionary stable strategies under different premises.
Let:

$$\varepsilon_1=(1-\lambda)(-C_1+F+\alpha\beta D) \tag{16}$$

$$\varepsilon_2=-(1-\lambda)C_1 \tag{17}$$

$$\varepsilon_3=(\alpha\beta+1-\alpha)W-B-R-(-\alpha\beta-\lambda+\alpha\lambda)T+(\lambda+\alpha-\alpha\lambda)F \tag{18}$$

$$\varepsilon_4=(\alpha\beta+1-\alpha)(W+T)-B-R+F \tag{19}$$

ε_1 represents the cost saved by the government through active regulation compared to passive regulation when non-compliant port companies choose to disguise and conceal. ε_2 represents the cost saved by the government through active regulation compared to passive regulation when non-compliant companies choose self-disclosure. ε_3 represents the additional benefits gained by non-compliant companies through self-disclosure compared to disguise and concealment when the government adopts passive regulation. ε_4 represents the additional benefits gained by non-compliant companies through self-disclosure compared to disguise and concealment when the government adopts active regulation.

According to the evolutionary game theory, an equilibrium point with $det\,\boldsymbol{J}>\boldsymbol{0}, tr\,\boldsymbol{J}<\boldsymbol{0}$ is the evolutionary stable point (ESS) of the system[15], an equilibrium point with $det\,\boldsymbol{J}<\boldsymbol{0}$ is the evolutionary saddle point of the system, and an equilibrium point with $det\,\boldsymbol{J}>\boldsymbol{0}, tr\,\boldsymbol{J}>\boldsymbol{0}$ is the evolutionary unstable point of the system. By conducting local stability analysis on the system's Jacobian matrix, four different equilibrium results can be obtained in specific scenarios, and the detailed analysis is as follows.

Scenario I: $\varepsilon_1<0, \varepsilon_3<0$, i.e., $C_1-F>\alpha\beta D>0$, $B+R>(\alpha\beta+1-\alpha)W+(\alpha\beta+\lambda-\alpha\lambda)T+(\lambda+\alpha-\alpha\lambda)F>0$. In this case, the point (0, 0) is the evolutionary stable point (ESS) of the system.

$\varepsilon_1<0$ means $\alpha\beta D<C_1-F$, and $\varepsilon_3<0$ means $(\alpha\beta+1-\alpha)W+(\alpha\beta+\lambda-\alpha\lambda)T+(\lambda+\alpha-\alpha\lambda)F<B+R$. In this case, only the equilibrium point (0,0) satisfies $det\,\boldsymbol{J}>\boldsymbol{0}, tr\,\boldsymbol{J}<\boldsymbol{0}$, making it the ESS of the system. When $\varepsilon_4<0$, the equilibrium points (0,1) and (1,0) satisfy $det\,\boldsymbol{J}<\boldsymbol{0}, tr\,\boldsymbol{J}$ is uncertain, making them evolutionary saddle points, while the equilibrium point (1,1) satisfies $det\,\boldsymbol{J}>\boldsymbol{0}, tr\,\boldsymbol{J}>\boldsymbol{0}$, making it an evolutionarily unstable point. When $\varepsilon_4>0$, the equilibrium points (0,1) and (1,1) satisfy $det\,\boldsymbol{J}<\boldsymbol{0}, tr\,\boldsymbol{J}$ is uncertain, making them evolutionary saddle points, and the equilibrium point (1,0) satisfies $det\,\boldsymbol{J}>\boldsymbol{0}, tr\,\boldsymbol{J}>\boldsymbol{0}$, making it an evolutionarily unstable point.

In this case, $\varepsilon_3<0$ indicates that the benefits obtained by fraudulent companies through concealment exceed those obtained through self-disclosure, leading the fraudulent companies to avoid choosing self-disclosure. The government aims to encourage self-disclosure by fraudulent companies through regulatory policies, but $\varepsilon_1<0$ indicates that the cost of active regulation by the government exceeds the cost of passive regulation, leading the government to choose passive regulation. Therefore, for both the government and companies, the lowest-cost choices are passive regulation and concealment, leading to potentially different evolutionary paths in strategy selection. However, the system will eventually stabilize at the ESS, representing (passive regulation, disguise), which is a situation the government does not want to see.

Scenario II: $\varepsilon_3>0$, i.e., $(\alpha\beta+1-\alpha)W+(\alpha\beta+\lambda-\alpha\lambda)T+(\lambda+\alpha-\alpha\lambda)F>B+R>0$. In this case, the point (0,1) is the evolutionary stable point (ESS) of the system.

When $\varepsilon_3>0$, i.e., $(\alpha\beta+1-\alpha)W+(\alpha\beta+\lambda-\alpha\lambda)T+(\lambda+\alpha-\alpha\lambda)F>B+R$, and $(\alpha\beta+1-\alpha)(W+T)+F>(\alpha\beta+1-\alpha)W+(\alpha\beta+\lambda-\alpha\lambda)T+(\lambda+\alpha-\alpha\lambda)F$ (because $\lambda<1$, $\lambda+\alpha-\alpha\lambda<1$), hence $(\alpha\beta+1-\alpha)(W+T)+F>B+R$, i.e., $\varepsilon_4>0$. In this case, only the equilibrium point (0,1) satisfies$det\,\boldsymbol{J}>\boldsymbol{0}, tr\,\boldsymbol{J}<\boldsymbol{0}$, making it the ESS of the system. When $\varepsilon_1<0$, the equilibrium points (0,0) and (1,1) satisfy $det\,\boldsymbol{J}<\boldsymbol{0}, tr\,\boldsymbol{J}$ is uncertain, making them evolutionary saddle points, and the equilibrium point (1,0) is an evolutionarily unstable point. When ε_1>0, the equilibrium points (1,0) and (1,1) satisfy $det\,\boldsymbol{J}<\boldsymbol{0}, tr\,\boldsymbol{J}$ is uncertain, making them evolutionary saddle points, and the equilibrium point (0,0) is an evolutionarily unstable point.

In this case, $\varepsilon_3>0$ indicates that the benefits obtained by fraudulent companies through self-disclosure exceed those obtained through concealment. Therefore, regardless of the regulatory strategy adopted by the government, fraudulent companies are willing to choose self-disclosure. This situation mainly arises because the reduction in fines and the reputation and public support obtained from taking carbon reduction measures such as shore power and LNG energy outweigh the additional costs incurred compared to choosing concealment over self-disclosure. For the government, the best outcome is for no regulation to be needed, and for fraudulent maritime and aviation companies to voluntarily choose self-disclosure.

Therefore, for both the government and companies, the lowest-cost choices are passive regulation and self-disclosure, leading to potentially different evolutionary paths in strategy selection. However, the system will eventually stabilize at the ESS, representing (passive regulation, self-disclosure), achieving a state of "governing by non-interference."

Scenario III: $\varepsilon_1 > 0, \varepsilon_4 < 0$, i.e., $\alpha\beta D > C_1 - F > 0$ and $B + R > (\alpha\beta + 1 - \alpha)(W + T) + F > 0$. In this case, the point (1, 0) is the evolutionary stable point (ESS) of the system.

When $\varepsilon_1 > 0$, i.e., $\alpha\beta D > C_1 - F$, and $\varepsilon_4 < 0$, $(\alpha\beta + 1 - \alpha)(W + T) + F < B + R$, while $(\alpha\beta + 1 - \alpha)W + (\alpha\beta + \lambda - \alpha\lambda)T + (\lambda + \alpha - \alpha\lambda)F < (\alpha\beta + 1 - \alpha)(W + T) + F$ (because $\lambda < 1$, $\lambda + \alpha - \alpha\lambda < 1$), it follows that $\varepsilon_3 < 0$. In this case, only the equilibrium point (1,0) satisfies $det\boldsymbol{J} > \mathbf{0}, tr\,\boldsymbol{J} < \mathbf{0}$, making it the ESS of the system. The equilibrium points (0,0) and (0,1) satisfy $det\boldsymbol{J} < \mathbf{0}, tr\,\boldsymbol{J}$ is uncertain, making them evolutionary saddle points, and the equilibrium point (1,1) satisfies $det\boldsymbol{J} > \mathbf{0}, tr\,\boldsymbol{J} > \mathbf{0}$, making it an evolutionarily unstable point in the system.

In this case, $\varepsilon_3 < 0$ and $\varepsilon_4 < 0$ indicate that the profits obtained by fraudulent maritime and aviation companies through concealment exceed those obtained through self-disclosure. As a result, even at the risk of facing high fines for being discovered and potential damage to their reputation, fraudulent companies would still choose to conceal their actions. $\varepsilon_1 > 0$ indicates that for the government, the benefits obtained from active regulation exceed those from passive regulation. This is mainly due to the fines imposed by active regulation and the avoidance of reputation damage outweighing the cost savings from passive regulation.

Therefore, for the government and companies, the lowest-cost choices are active regulation and concealment. While the strategy selection may lead to different evolutionary paths, it will eventually stabilize at the ESS, representing (active regulation, disguise). This is a situation that the government does not want to see.

Scenario VI: $\varepsilon_2 > 0, \varepsilon_4 < 0$, i.e., $C_1 < 0, B + R > (\alpha\beta + 1 - \alpha)(W + T) + F > 0$. In this case, the system does not have an evolutionarily stable strategy (ESS).

Even though $\varepsilon_2 > 0$ and $\varepsilon_4 < 0$ can satisfy $det\boldsymbol{J} > \mathbf{0}, tr\,\boldsymbol{J} < \mathbf{0}$ at the equilibrium point (1,1), achieving the Evolutionarily Stable Strategy (ESS) for the system, $\varepsilon_2 > 0$ implies $C_1 < 0$, where C_1 represents the cost of government active regulatory input, and it must be a positive real number. Therefore, there is no Evolutionarily Stable Strategy (ESS).

4.Numerical simulation analysis

This section utilizes MATLAB 2019a to numerically simulate the equilibrium points under various scenarios of evolutionary games in Sections 3.2, analyzing the evolutionary trajectories from different initial values to the equilibrium points. The time period in the figures is [0, 100], and the initial values of x and y are set as [0.2, 0.8], [0.4, 0.6], [0.6, 0.4], and [0.8, 0.2]. The horizontal axis represents the proportion x of proactive regulation chosen by the government, and the vertical axis represents the proportion y of self-disclosure chosen by companies.

From Figure 1, it can be observed that the stable strategy for Scenario I is (0, 0), i.e., (passive regulation, Disguise). Initially, a certain proportion of the government choose proactive regulation, but they realize that the cost of proactive regulation is too high, so the government tends to prefer the higher benefits of passive regulation. Companies that initially choose self-disclosure quickly discover that the fines imposed by the government and the losses from public reporting are not high, and consequently, driven by profit, they swiftly shift toward violation concealment. The media's participation is very low, and both the government and the companies choose strategies that are unfavorable to the media[16].

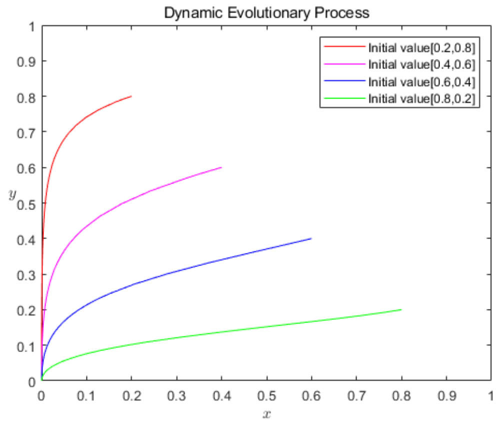

Fig. 1. Dynamic Evolution Process of Scenario I

From Figure 2, it can be seen that the stable strategy for Scenario II is (0, 1), i.e., (passive regulation, self-disclosure). Initially, a certain proportion of companies choose violation concealment, but profit-driven companies quickly realize that even considering factors such as fine subsidies, self-disclosure brings in more total profit. Therefore, they swiftly shift towards self-disclosure. A certain proportion of the government initially chooses proactive regulation, but in the long-term evolution, they find that companies tend towards self-disclosure. Continuing to choose proactive regulation becomes too costly, so the government will relax its regulation of companies and evolve towards passive regulation, ultimately achieving a result of "governing by doing nothing".

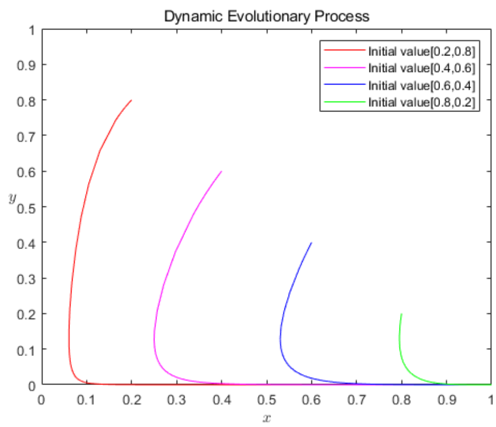

Fig. 2. Dynamic Evolution Process of Scenario II

From Figure 3, it can be seen that the stable strategy for Scenario III is (1, 0), i.e., (proactive regulation, Disguise). Initially, a certain proportion of companies in the group choose self-disclosure, but profit-driven companies quickly realize that the losses from government fines and media exposure are not high, while early disclosure will bring additional losses. Violating companies tend to conceal violations, despite facing media scrutiny and government fines, because overall gains are higher. When the government engages in passive regulation, the income from fines on companies is very low, while the loss of government credibility is very high. The cost of passive regulation is higher, so the government will tend towards proactive regulation.

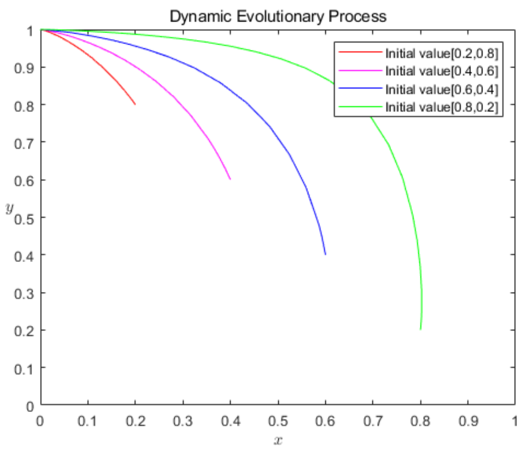

Fig. 3. Dynamic Evolution Process of Scenario III

Similarly, numerical simulation of the dynamic punishment mechanism in the evolutionary game model in section 4.2 yields Figure 4. From the figure, it can be seen that regardless of the initial values of the government group and the group of violative airlines, the evolutionary path will spiral towards the end point, near (0.26, 0.06). At this point, the government and the group of companies reach an equilibrium and stable state in the evolutionary game process.

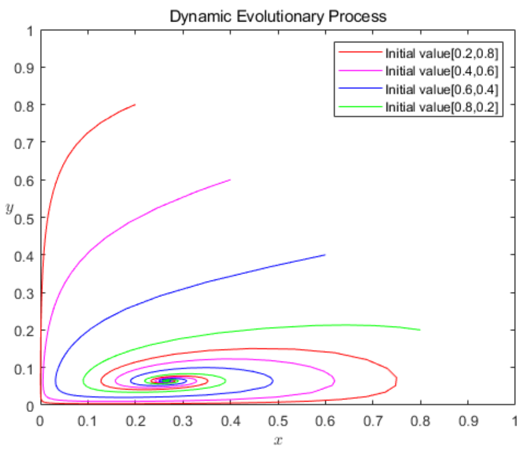

Fig. 4. Dynamic Evolution Process of Scenario IV

5.Conclusions

This article conducts an evolutionary game analysis of government environmental regulation and emission reduction strategies for violative port and shipping companies. It proposes the following suggestions for the formulation and implementation of environmental regulations in China:

(1) For the government, increasing the fine on violative port and shipping companies is an effective means to promote the smooth implementation of environmental regulations. Environmental pollution is one of the important issues that China urgently needs to address. If violative port and shipping companies choose to conceal violations, they will face high fines from the government and losses from media exposure. Confronted with these costs, violative companies are likely to voluntarily disclose violations and undergo production suspension for rectification. The income generated from fines and active media participation can compensate for the costs of government supervision.

(2) For violative port and shipping companies, the government's provision of subsidies for voluntary disclosure is a necessary condition to promote environmentally friendly production. Companies that voluntarily disclose violations will face temporary production suspensions and incur certain losses. If the government can provide reasonable subsidies, the proportion of violative companies choosing voluntary disclosure will increase. They will realize that timely voluntary disclosure offers higher profit potential, thus prompting them to voluntarily disclose violations.

(3) Active media participation can significantly reduce government supervision costs and encourage violative companies to voluntarily disclose violations. In matters of environmental issues, the media and the government should share a common goal. The media can participate as a force within the government's environmental regulation policy formulation and implementation. For example, the media can report violative port and shipping companies that violate regulations and conceal violations to the local government, significantly increasing the probability of successful passive supervision by the government and reducing government supervision costs. Media outlets such as online platforms and newspapers can use exposure to exercise public scrutiny over port and shipping companies, prompting violative companies to choose voluntary disclosure in order to protect their reputations.

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