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CARBON EMISSION OPTIMIZATION METHOD FOR OPERATING TUNNELS: AN EVOLUTIONARY GAME-BASED ANALYSIS STUDY

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Abstract: For the contradiction between the carbon reduction benefits and economic costs of operating tunnels' carbon reduction measures and government incentive policies, this paper establishes an evolutionary game model between the government and tunnel operators, and analyzes the evolutionary paths of strategic choices between the two game sides by replicating the dynamic equations. Through numerical simulation, the influence of key parameters such as incentive policy and carbon reduction cost on the balance of the game is quantitatively analyzed. This study can provide a decision-making basis for the implementation of tunnel carbon reduction measures and the formulation of carbon reduction policies.

Keywords: Low-carbon tunnel, Evolutionary game, Incentive policy, Carbon emission optimization

1. INTRODUCTION

Global climate warming is becoming increasingly severe, posing a significant threat to human survival and development. There is an urgent need for effective control of greenhouse gases, primarily represented by carbon dioxide. Currently, the transportation sector accounts for approximately 23% of annual global greenhouse gas emissions and will continue growing with global industrialization and urbanization. Tunnels are an essential component of the transportation industry. As high-energy-consuming transportation infrastructure(Pritchard and Preston, 2018), the carbon emissions produced during tunnel construction and operation have become increasingly prominent. It has become a key research focus under the "dual carbon" goals.

The operation and maintenance phase is the longest phase during the whole life of a tunnel, accounts for more than half of the total carbon emissions throughout its life cycle(Song et al., 2024a). Carbon reduction during this phase is an important step towards the realization of low-carbon or even zero-carbon tunnels. Currently, research on carbon emissions during tunnel operation and maintenance phase primarily focuses on carbon accounting methods and carbon reduction measures. In terms of carbon accounting methods, the object of study has gradually evolved from the single tunnel to the tunnel group. The method of research has gradually developed from traditional accounting methods to digital methods(Hussain et al., 2023; Liu et al., 2024). In terms of carbon reduction measures, the underlying logic can be mainly divided into two categories: reducing carbon sources and increasing carbon sinks. The reduction of carbon sources is primarily realized by the combination of energy-saving and carbon-reducing measures in tunnel lighting(Cengiz and Cengiz, 2018; Shen et al., 2022; Song et al., 2024b), ventilation(Beiza, 2024; Wang et al., 2023), and other systems. Increasing carbon sinks is mainly achieved by planting trees within the tunnel site(Jiang et al., 2022), installing photovoltaic and wind power generation systems

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to utilize renewable energy sources, etc. The research, development, application, and promotion of these carbon reduction technologies are key to achieving low-carbon and zero-carbon goals.

However, current research pays little attention to the relationship between the economic investment and carbon reduction effects of these carbon reduction measures. These measures often have high investment costs, long payback periods. Without additional incentives, they are not economically attractive, and have certain investment barriers. As a result, tunnel operators might prefer to adopt traditional tunnel operation technologies that are low-cost, low-risk, and offer larger profit margins, rather than increasing investment in carbon reduction measures for the sake of reducing carbon emissions. To promote the development and application of carbon reduction technologies in tunnel operations, many governments have implemented incentive measures such as financial subsidies, tax benefits, and market-based mechanisms. There exists a conflict of interest between the government and tunnel operators. The incentives provided by the Government will directly affect the costs and benefits of carbon reduction for tunnel operators. The behavior of tunnel operators will also affect the effectiveness of the government's incentives and the level of carbon emissions in the society. In general, the goal of government is to achieve social emission reduction targets at the lowest cost, while tunnel operators aim to maximize their benefits with lowest costs. It is necessary to find a suitable optimization method to balance the conflicting interests of both sides and achieve a win-win situation.

Game theory, a discipline belonging to operations research, is an important tool used for studying competitive phenomena. It expresses participants' strategic choices and their payoffs using formulas, predicting their behaviors through formula derivation, and conducting result analysis and optimization. Evolutionary game theory, a further development of game theory, is a decision-making method based on dynamic theory. It can analyze and evaluate the behavioral choices and decisions of self-interested game participants with limited rationality and asymmetric information over time through continuous learning and adjustment. Evolutionary game theory is often used to analyze the dynamics of interactions between different groups and is widely used in fields such as energy(Haoyang et al., 2022; Qiao et al., 2024), building(Fan and Hui, 2020; Yang and Liu, 2024), agriculture(Mu et al., 2025), transportation(Guo et al., 2021), and supply chain management(Huo et al., 2022; Wan et al., 2022). Evolutionary game theory shows significant advantages in analyzing the interaction of carbon emission reduction strategies between government and enterprises. By establishing evolutionary game models, these studies analyze the evolutionary stabilization strategies of the game players and the influence of parameter changes on strategy selection, thus providing a basis for policy formulation. On this basis, some scholars have combined evolutionary games with other theoretical methods to provide multi-dimensional theoretical support for evolutionary game models (Li and Zhang, 2024; Xue et al., 2024).

The characteristics of limited rationality and dynamic evolution of evolutionary games align with the behavioral patterns and decision-making characteristics of the government and tunnel operators. However, the evolutionary game theory has not yet been applied to tunnel operation and maintenance optimization.

Therefore, this paper establishes an evolutionary game model between the government and tunnel operators, considering static reward and punishment mechanisms of government, aiming to analyzes the evolutionary path of strategic choices for both players and the impact of key parameters on the game equilibrium. The rest of this paper is structured as follows: **Section 2** constructs the evolutionary game model. **Section 3** analyzes the equilibrium point and evolutionary path of the model. **Section 4** conducts numerical simulation. **Section 5** summarizes the content of this paper. The research findings can provide references for the government to customize carbon reduction incentive policies and for tunnel operators to adopt carbon reduction measures.

2. EVOLUTIONARY GAME MODEL

2.1. Model Assumptions

The evolutionary game model between the government and tunnel operator is shown in ***Figure 1***, with the following assumptions:

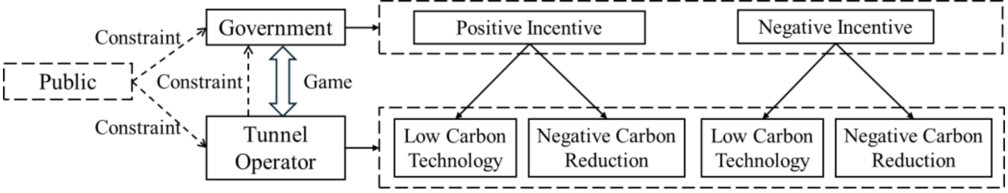


Figure 1. *Evolutionary Game Model of Government and Tunnel Operator*

Assumption 1: The players of the evolutionary game are the government and tunnel operators. Each player has limited rationality, can make independent decisions to maximize their own benefits, and will continuously adjust their strategies based on actual situations during the game process.

Assumption 2: The government has two strategies, “positive incentives” and “negative incentives”, with probabilities x and 1 - x respectively. The "active incentive" strategy includes both subsidies and fines. When the government chooses a positive incentive strategy, it will provide additional subsidies L to tunnel operators adopting low carbon technologies, and impose fines F to tunnel operators adopting conventional technologies. To maintain the incentive policy, the government will generate regulatory costs C caused by the consumption of human, financial, and material resources. When the government chooses passive incentive, it will take a laissez-faire attitude without investment or supervision, neither subsidizing tunnel operators who adopt low-carbon technologies nor penalizing those who use traditional technologies.

Assumption 3: Tunnel operators have two strategies, "adopting carbon reduction technology" and "adopting traditional technology," with probabilities y and 1-y respectively. "Adopting carbon reduction technology" means that tunnel operators choose more environmentally friendly, high-performance, and durable materials during tunnel design, improve material utilization, and adopt more advanced construction and operation methods for energy-saving and carbon reduction. This will incur certain additional initial costs P and produce additional benefits G. When the government adopts positive incentives, tunnel operators will receive additional government subsidies L. "Adopting traditional technology" means that tunnel operators, due to high costs of low-carbon technologies and unclear additional benefits, do not invest additional costs and choose to use traditional technologies, taking a laissez-faire attitude towards carbon emissions, often exceeding the carbon quota set by the government. When the government adopts positive incentives, they will be fined F.

Assumption 4: This study stipulates that all external impacts of operators' behavior are borne by the government. Regardless of whether the government takes incentive measures, when tunnel operators actively use low-carbon technologies, the government obtains corresponding social benefits M. When tunnel operators use traditional technologies, the government suffers corresponding social losses N.

Assumption 5: There are certain constraints among the public, operators, and the government, mainly including the following three types: (1) Tunnel operators constraints on the government: When tunnel operators adopt carbon reduction technologies, if the government does not provide incentives or any subsidy measures, the government will incur reputation loss and coordination costs D_1; (2) Public constraints on operators: When tunnel operators use traditional technologies, their passive carbon reduction behavior will cause environmental pollution, resulting in public image loss D_2 for the tunnel operators; (3) Public constraints on the government: When the government adopts negative incentives, it will cause environmental pollution, leading to reputation loss D_3 for the government.

2.2. MODEL BUILDING

Based on the above assumptions and analysis, the payoff matrix for the game between the government and tunnel operators is shown in ***Table 1***.

Table 1. *Payment matrix of the game between the government and the tunnel operator*

Players		Tunnel operators	
		Low-carbon technology y	Traditional technology 1-y
Government	Positive incentives x	$M-C-L, G+L-P$	$F-C-N, -F-D_2$
	Negative incentives 1-x	$M-D_1-D_3, G_1-P$	$-N-D_3, -D_2$

The expected payoff for the government when choosing positive incentives is:

$$U_{1x} = y(M-C-L) + (1-y)(F-C-N) \tag{1}$$

The expected payoff for the government when choosing negative incentives is:

$$U_{1n} = y(M-D_1-D_3) + (1-y)(-N-D_3) \tag{2}$$

The average expected payoff for the government using a mixed strategy is:

$$\overline{U_1} = xU_{1x} + (1-x)U_{1n} \tag{3}$$

The expected payoff for tunnel operators when choosing low-carbon technology is:

$$U_{2y} = x(G + L - P) + (1 - x)(G - P) \tag{4}$$

The expected payoff for tunnel operators when choosing traditional technology is:

$$U_{2n} = x(-F - D_2) + (1 - x)(-D_2) \tag{5}$$

The average expected payoff for tunnel operators using a mixed strategy is:

$$\overline{U_2} = yU_{2y} + (1 - y)U_{2n} \tag{6}$$

The replicator dynamics equations are a set of dynamic equations that reflect the behavioral trajectories of participating subjects as they change over time. According to evolutionary game theory, the replicator dynamics equation for government is shown in Eq (7):

$$F(x) = x(U_{1x} - \overline{U_1}) = x(1 - x)[y(D_1 - L - F) + (F - C + D_3)] \tag{7}$$

Similarly, the replicator dynamics equation for tunnel operators is shown in Eq (8):

$$F(y) = y\left(U_{2y} - \overline{U_2}\right) = y(1 - y)[x(L + F) + (G - P + D_2)] \tag{8}$$

By combining these two replicator dynamics equations, we can obtain a two-dimensional dynamic system that reflects the behavioral evolution of the government and tunnel operators over time:

$$\begin{cases} F(x) = x(1 - x)[y(D_1 - L - F) + (F - C + D_3)] \\ F(y) = y(1 - y)[x(L + F) + (G - P + D_2)] \end{cases} \tag{9}$$

3. MODEL ANALSIS

3.1. Equilibrium Point Analysis

The replication dynamic equations describe the group dynamics in an evolutionary system involving the government and tunnel operators. When the expected payoffs of different strategies are equal, the system remains in a stable state, resulting in equilibrium points. Setting $F(x) = \frac{dx}{dt} = 0$ and $F(y) = \frac{dy}{dt} = 0$, we can obtain five equilibrium points for the system: $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$, and (x^*, y^*), where $x^* = \frac{-(G-P+D_2)}{L+F}$, $y^* = \frac{-(F-C+D_3)}{D_1-L-F}$, and $0 < x^*, y^* < 1$.

According to Friedman's research, equilibrium points of the system do not inherently imply stability. Their local stability must be evaluated via the Jacobian matrix. For a two-dimensional dynamical system, the Jacobian matrix J is defined as follows:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{10}$$

Where the Jacobian components are defined as: $a_{11} = (1 - 2x)[y(D_1 - L - F) + (F - C + D_3)]$, $a_{12} = x(1 - x)(D_1 - L - F)$, $a_{21} = y(1 - y)(L + F)$, $a_{22} = (1 - 2y)[x(L + F) + (G - P + D_2)]$. The equilibrium is asymptotically stable (ESS) iff: $Det(J) > 0$ and $Tr(J) = a_{11} + a_{22} < 0$. An equilibrium point is asymptotically stable and considered an Evolutionary Stable Strategy (ESS) point of the system if and only if the corresponding Jacobian matrix J simultaneously satisfies: $Det(J) > 0$ and $Tr(J) = a_{11} + a_{22} < 0$. If $Det(J) > 0$ and $Tr(J) = a_{11} + a_{22} > 0$, then the equilibrium point is unstable. If $Det(J) < 0$ and $Tr(J) = 0$ or is indeterminate, then the equilibrium point is a saddle point.

To determine the stability of the system's equilibrium points, the determinant $Det(J)$ and trace $Tr(J)$ of the Jacobian matrix J must be computed at each of the five equilibrium points. The values of $Det(J)$ and $Tr(J)$ for the Jacobian matrices at all system equilibrium points are summarized in ***Table 2***.

Due to uncertain parameter values, this system can exhibit 12 cases as shown in ***Table 3***.

3.2. Evolutionary Trend Analysis

Based on the local stability and corresponding evolutionary phase diagrams of equilibrium points under different parameter combinations in ***Table 3***, we will discuss the evolutionary trends of government strategies, tunnel operator strategies, and the combination of both players' strategies.

Table 2. *$Det(J)$ and $Tr(J)$ at the local equilibrium point*

(x, y)	$Det(J)$	$Tr(J)$
$(0,\ 0)$	$(F-C+D_3)(G-P+D_2)$	$(F-C+D_3)+(G-P+D_2)$
$(0,\ 1)$	$-(D_1-L-C+D_3)(G-P+D_2)$	$(D_1-L-C+D_3)-(G-P+D_2)$
$(1,\ 0)$	$-(F-C+D_3)(L+F+G-P+D_2)$	$-(F-C+D_3)+(L+F+G-P+D_2)$
$(1,\ 1)$	$(D_1-L-C+D_3)(L+F+G-P+D_2)$	$-(D_1-L-C+D_3)-(L+F+G-P+D_2)$
(x^*, y^*)	$-x^*(1-x^*)y^*(1-y^*)(D_1-L-F)(L+F)$	0

Table 3. *Summary of local stability at equilibrium points and corresponding evolutionary phase diagrams under different parameter combinations*

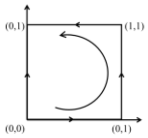
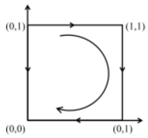
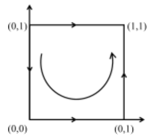
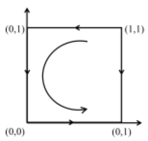
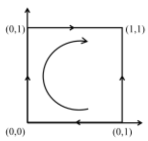
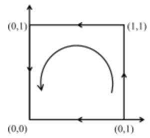
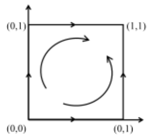
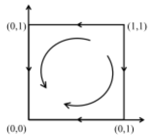
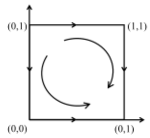
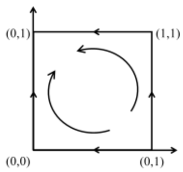
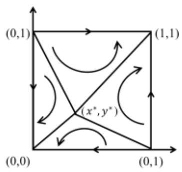
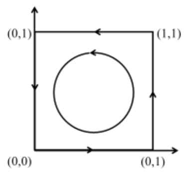
Equilibrium Point	Case 1			Case 2			Case 3		
	$G-P>-D_2$ $G+L-P>-F-D_2$ $M-D_1-D_3>M-C-L$ $-N-D_3<F-C-N$			$G-P<-D_2$ $G+L-P<-F-D_2$ $M-D_1-D_3<M-C-L$ $-N-D_3>F-C-N$			$G-P<-D_2$ $G+L-P>-F-D_2$ $M-D_1-D_3<M-C-L$ $-N-D_3<F-C-N$		
	$Det(J)$	$Tr(J)$	Stability	$Det(J)$	$Tr(J)$	Stability	$Det(J)$	$Tr(J)$	Stability
(0,0)	+	+	Unstable Point	+	−	Ees Point	−	±	Saddle Point
(0,1)	+	−	Ees Point	+	+	Unstable Point	+	+	Unstable Point
(1,0)	−	±	Saddle Point	−	±	Saddle Point	−	±	Saddle Point
(1,1)	−	±	Saddle Point	−	±	Saddle Point	+	−	Ees Point
(x^*, y^*)	Nonexistent Equilibrium			Nonexistent Equilibrium			Nonexistent Equilibrium		
Evolutionary Phase Diagram									
Equilibrium Point	Case 4			Case 5			Case 6		
	$G-P<-D_2$ $G+L-P<-F-D_2$ $M-D_1-D_3>M-C-L$ $-N-D_3<F-C-N$			$G-P>-D_2$ G+$L-P>-F-D_2$ $M-D_1-D_3<M-C-L$ $-N-D_3>F-C-N$			$G-P<-D_2$ $G+L-P>0-F-D_2$ $M-D_1-D_3>M-C-L$ $-N-D_3>F-C-N$		
	$Det(J)$	$Tr(J)$	Stability	$Det(J)$	$Tr(J)$	Stability	$Det(J)$	$Tr(J)$	Stability
(0,0)	−	±	Saddle Point	−	±	Saddle Point	+	−	Ees Point
(0,1)	−	±	Saddle Point	−	±	Saddle Point	−	±	Saddle Point
(1,0)	+	−	Ees Point	+	+	Unstable Point	+	+	Unstable Point
(1,1)	+	+	Unstable Point	+	−	Ees Point	−	±	Saddle Point
(x^*, y^*)	Nonexistent Equilibrium			Nonexistent Equilibrium			Nonexistent Equilibrium		
Evolutionary Phase Diagram									

Table 3 *(Continued)*

Equilibrium Point	Case 7			Case 8			Case 9		
	$G-P>-D_2$ $G+L-P>-F-D_2$ $M-D_1-D_3<M-C-L$ $-N-D_3<F-C-N$			$G-P<-D_2$ $G+L-P<-F-D_2$ $M-D_1-D_3>M-C-L$ $-N-D_3>F-C-N$			$G-P<-D_2$ $G+L-P<-F-D_2$ $M-D_1-D_3<M-C-L$ $-N-D_3<F-C-N$		
	$Det(J)$	$Tr(J)$	Stability	$Det(J)$	$Tr(J)$	Stability	$Det(J)$	$Tr(J)$	Stability
(0,0)	+	+	Unstable Point	+	−	Ees Point	−	±	Saddle Point
(0,1)	−	±	Saddle Point	−	±	Saddle Point	+	+	Unstable Point
(1,0)	−	±	Saddle Point	−	±	Saddle Point	+	−	Ees Point
(1,1)	+	−	Ees Point	+	+	Unstable Point	−	±	Saddle Point
(x^*,y^*)	Nonexistent Equilibrium			Nonexistent Equilibrium			Nonexistent Equilibrium		
Evolutionary Phase Diagram									
Equilibrium Point	Case 10			Case 11			Case 12		
	$G-P>-D_2$ $G+L-P>-F-D_2$ $M-D_1-D_3>M-C-L$ $-N-D_3>F-C-N$			$G-P<-D_2$ $G+L-P>-F-D_2$ $M-D_1-D_3<M-C-L$ $-N-D_3>F-C-N$			$G-P<-D_2$ $G+L-P>-F-D_2$ $M-D_1-D_3>M-C-L$ $-N-D_3<F-C-N$		
	$Det(J)$	$Tr(J)$	Stability	$Det(J)$	$Tr(J)$	Stability	$Det(J)$	$Tr(J)$	Stability
(0,0)	−	±	Saddle Point	+	−	Ees Point	−	±	Saddle Point
(0,1)	+	−	Ees Point	+	+	Unstable Point	−	±	Saddle Point
(1,0)	+	+	Unstable Point	+	+	Unstable Point	−	±	Saddle Point
(1,1)	−	±	Saddle Point	+	−	Ees Point	−	±	Saddle Point
(x^*,y^*)	Center Point			Center Point			Nonexistent Equilibrium		
Evolutionary Phase Diagram									

3.2.1. Analysis of Government Strategy Space Evolution Trends

For the government, whenever the payoff from proactive incentive strategies consistently exceeds that of passive incentive strategies, specifically when both conditions $M-C-L>M-D_1-D_3$ and $-N-D_3<F-C-N$ hold (Case 3, 7, and 9), the government invariably converges to proactive incentives regardless of initial conditions or tunnel operators' strategy evolution. This is because: $D_1+D_3>L+C$ indicates that the constraints from tunnel operators and the public on the government are greater than the costs required for the government's positive incentives. $F-C+D_3>0$ indicates that the fines F obtained by the government choosing positive incentives can cover the regulatory costs C, while also avoiding reputation loss D_3, resulting in a positive net benefit. Therefore, it is more suitable for the government to choose a positive incentive strategy. Conversely, when $M-C-L<M-D_1-D_3$ and $-N-D_3>F-C-N$ (Case 6, 8, 10), the government will choose a negative incentive strategy regardless of the initial state and how the tunnel operator's strategy evolves.

For Case 1, 2, 4, and 5, the government's incentive strategy is related to the tunnel operator's strategy choice. When the probability of tunnel operators choosing low-carbon technology is greater than y^*, the evolutionary trend of the government's strategy always tends towards positive incentives. When the probability of tunnel operators choosing low-carbon technology is less than y^*, the evolutionary trend of the government's strategy always tends towards negative incentives.

3.2.2. Analysis of Tunnel operator Strategy Space Evolution Trends

For tunnel operators, if the benefits of adopting low-carbon technology are greater than those of using traditional technology, specifically when both conditions $G - P > -D_2$and $G + L - P > -F - D_2$ hold (Case 1, 5, 7, and 10), tunnel operators will choose to adopt low-carbon technology regardless of the initial state and how the government's strategy evolves. This is because: $G - P > -D_2$ indicates that without considering government rewards or punishments, the benefits for tunnel operators adopting low-carbon technology are greater than passive carbon reduction. $G + L - P > -F - D_2$ indicates that regardless of which incentive strategy the government chooses, the benefits for tunnel operators adopting low-carbon technology are always greater than those of passive carbon reduction. Therefore, it is more suitable for tunnel operators to choose low-carbon technology. Conversely, when $G - P < -D_2$ and $G + L - P < -F - D_2$ (Case 2, 4, 8, and 9), tunnel operators will choose to adopt traditional technology regardless of the initial state and how the government's strategy evolves.

For Case 3 and 7, the tunnel operators' strategy choice is related to the government's strategy choice. When the probability of the government adopting a positive incentive strategy is greater than x^*, the evolutionary trend of tunnel operators always tends towards adopting low-carbon technology. When the probability of the government choosing a positive incentive strategy is less than x^*, the evolutionary trend of tunnel operators always tends towards adopting traditional technology.

3.2.3. Analysis of Government-Tunnel Operator Strategy Space Evolution Trends

According to the above analysis, the evolutionary path of the system is from (0,0) to (1,0) to (0,1) to (1,1). This means it starts with the worst equilibrium strategy combination (government negative incentives, tunnel operators using traditional technology), gradually evolving to the second-worst equilibrium (government positive incentives, tunnel operators using traditional technology), then to the second-best equilibrium (government negative incentives, tunnel operators using low-carbon technology), and finally to the best equilibrium (government positive incentives, tunnel operators using low-carbon technology). The system reaches an optimal equilibrium state (ESS) if and only if: tunnel operators' payoffs from adopting low-carbon technology and government incentive subsidies are sufficiently high, and constraints imposed by the public and tunnel operators on the government are sufficiently strong.

Therefore, whether the optimal equilibrium becomes the final evolutionary equilibrium depends crucially on the government. If the benefits of the government adopting a positive incentive strategy are always greater than those of adopting a negative incentive strategy, only a second-best equilibrium can be achieved in this game. When the benefits and government incentive effects for tunnel operators adopting low-carbon technology are both ineffective, the evolutionary result can only be the worst or second-worst equilibrium. When the benefits and government incentive effects for tunnel operators adopting low-carbon technology are lacking, but the constraint mechanism for tunnel operators using traditional technology still exists, the system cannot achieve the optimal evolutionary equilibrium. However, for tunnel operators, the second-best evolutionary equilibrium can be pursued by increasing the intensity of punishment.

4. NUMERICAL SIMULATION

To more intuitively reflect the evolutionary mechanism between the government and tunnel operators, this section will assign values to the model parameters under different scenarios, thereby revealing the evolution process of the initial state and the sensitivity of key factors. Assume that in the initial state, the probability of both the government and tunnel operators choosing each strategy is 0.5. Let: L = 40, F = 15, C = 30, P = 100, G = 50, M = 80, N = 70, D_1 = 65, D_2 = 30, D_3 = 10. The parameter design satisfies Case 11 in Table 3: $G - P < -D_2$, $G + L - P > -F - D_2$, $M - D_1 - D_3 < M - C - L$, $-N - D_3 > F - C - N$. The simulation results of the strategy evolution for the government and tunnel operators are shown in ***Figure 2***. The strategy choices of both players will converge to two equilibrium points: (0, 0) and (1, 1). Next, sensitivity simulation analysis of external variables will be conducted based on this.

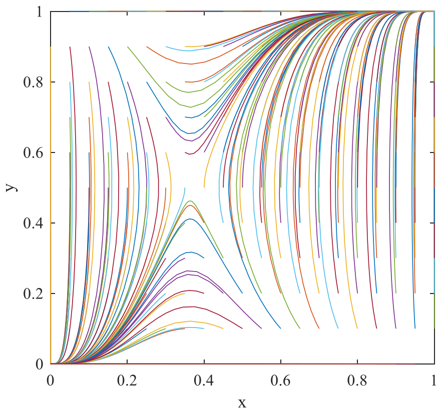


Figure 2. *Simulation results of strategy evolution of government and tunnel operator for L=40, F=15, C=30, P=100, G=50, D_1 = 65, D_2 = 30, D_3 = 10*

4.1. Government subsidies and fines

While keeping other parameters constant, simulations were conducted six times by setting the government subsidy L to 30, 35, 40, 45, 50, and 55 respectively. The simulation results of the evolutionary path of strategy selection for both the government and tunnel operators are shown in ***Figure 3***. It indicates that the government subsidy L is one of the key factors influencing the evolutionary strategies of both players in the game. When the subsidy L is relatively small ($L \leqslant 40$), the behaviors of both the government and tunnel operators eventually evolve towards adopting positive incentives and low-carbon technology. When L = 30, the probability of both players adopting positive strategies approaches 1 at the fastest rate. When the subsidy L is relatively large ($L \geqslant 50$), the behaviors of both the government and tunnel operators eventually evolve towards adopting negative incentives and traditional technology. As the tunnel subsidy intensity increases, the convergence speed of both players accelerates.

While keeping other parameters constant, simulations were conducted six times by setting the government fines F to 20, 30, 40, 50, 60, and 70 respectively. The simulation results of the evolutionary path of strategy selection for both the government and tunnel operators are shown in ***Figure 4***. As the government's fines F gradually increases, the government's evolutionary stable strategy shifts from negative incentives to positive incentives, and the speed at which the probability of adopting a positive incentive strategy approaches 1 accelerates. Too small fines lead to tunnel operators choosing traditional technology. However, the rate at which tunnel operators' probability of adopting carbon-reduction technologies tends to 1 does not always increase with fines. This probability reaches its fastest convergence rate when F = 25.

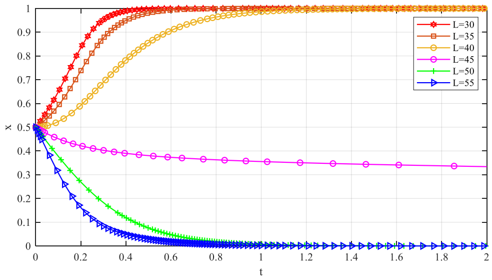
Lower subsidies reduce the total cost of government positive incentives, increasing the government's willingness to provide such incentives. Higher subsidies increase the government's financial pressure, decreasing its willingness to offer positive incentives. A small fine F cannot provide sufficient driving force for both parties to evolve towards positive carbon reduction strategies. Excessively high fines F can have a counterproductive effect on the time it takes to reach evolutionary equilibrium. Therefore, it is necessary to formulate appropriate subsidy and fine levels based on actual situations, which may achieve twice the result with half the effort. It should be noted that the convergence rate of tunnel operators is greater than that of the government. This indicates that tunnel operators have a higher parameter sensitivity to these measures. It also suggests that the reward and punishment mechanism is an effective means of incentivizing tunnel operators.

4.2. Carbon Reduction Technology Cost P and Efficiency Gain G

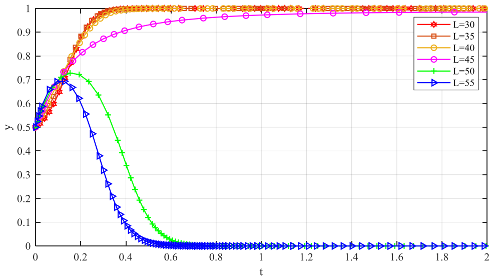
While keeping other parameters constant, simulations were conducted six times by setting the carbon reduction technology cost P to 80, 90, 100, 110, 120, and 130 respectively. The simulation results of the evolutionary path of strategy selection for both the government and tunnel operators are shown in ***Figure 5***. When $P \leqslant 100$, both the government and tunnel operators' strategies are positive, and the system's stabilization speed accelerates as P decreases. When $P \geqslant 110$, both the government and tunnel operators' strategies are negative, and the system's stabilization speed accelerates as P increases.

While keeping other parameters constant, simulations were conducted six times by setting the carbon reduction technology efficiency gain G to 35, 40, 45, 50, 55, and 60 respectively. The simulation results of the evolutionary path of strategy selection for both the government and tunnel operators are shown in ***Figure 6***. When G ⩾ 45, both the government and tunnel operators' strategies are positive, and the system's stabilization speed accelerates as G increases. When G ⩽ 40, both the government and tunnel operators' strategies are negative, and the system's stabilization speed accelerates as G decreases.

Reducing the cost P and increasing the efficiency gain G can enhance their willingness to adopt carbon reduction measures. Additionally, the stabilization rate of tunnel operators is significantly higher than that of the government. Tunnel operators have a higher parameter sensitivity to them.

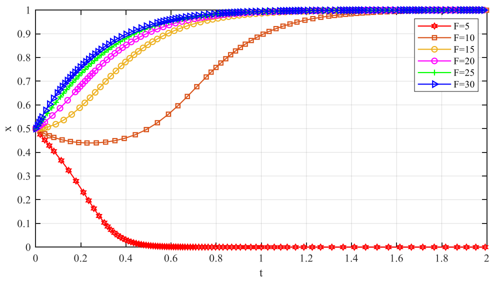


(a) Impact on government's strategy

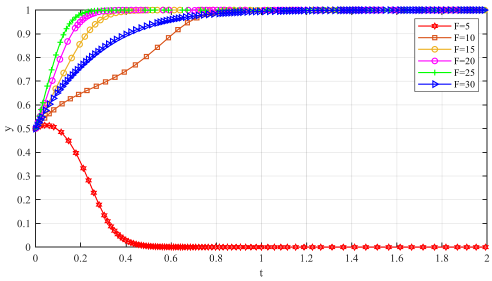


(b) Impact on tunnel operators' strategy

Figure 3. *Impact of government subsidy L to tunnel operators adopting low-carbon technologies on the evolutionary strategies of both sides of the game*

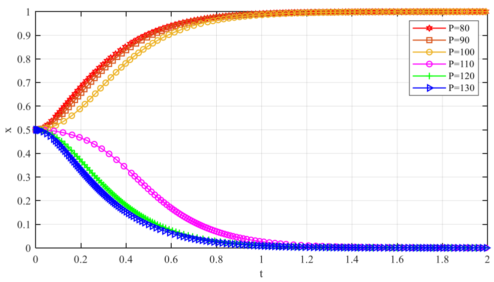


(a) Impact on government's strategy

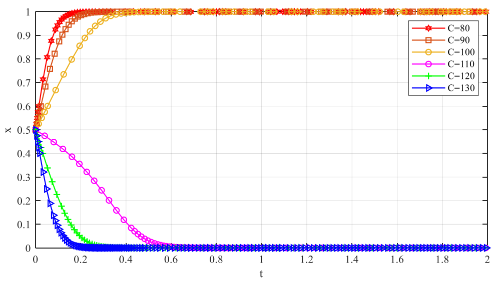


(b) Impact on tunnel operators' strategy

Figure 4. *Impact of government fines F to tunnel operators adopting traditional technologies on the evolutionary strategies of both sides of the game*

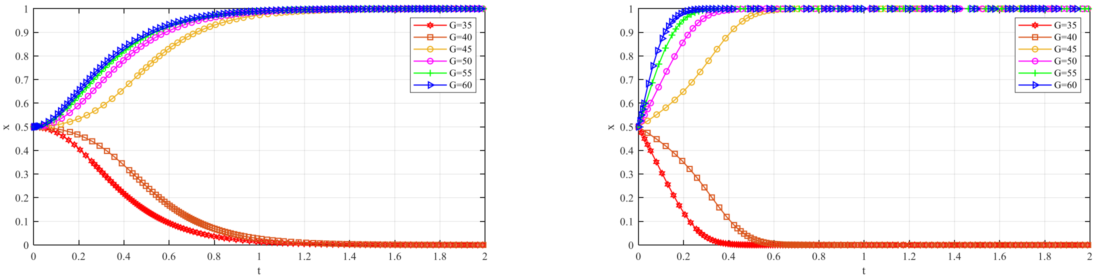


(a) Impact on government's strategy



(b) Impact on tunnel operators' strategy

Figure 5. *Impact of carbon-reduction technology costs P on the evolutionary strategies of both sides of the game*



(a) Impact on government's strategy

(b) Impact on tunnel operators' strategy

Figure 6. *Impact of carbon-reduction technology efficiency gain G on the evolutionary strategies of both sides of the game*

5. CONCLUSION

In summary, this paper establishes an evolutionary game model between the government and tunnel operators. Through replicator dynamic equations, it analyzes the evolutionary path of strategic choices for both players. Through numerical simulation, it analyzes the impact of key parameters on the game equilibrium. The main conclusions are as follows:

(1) The government's strategy choice is the key factor in determining whether the system can achieve optimal equilibrium. Only when the government adopts a positive incentive strategy can the system possibly converge to the optimal equilibrium of (positive incentive, adopting carbon reduction measures); otherwise, the system will fall into a suboptimal equilibrium state of (negative incentive, adopting carbon reduction measures).

(2) Tunnel operators typically exhibit faster convergence speeds than governments. At the national level, long-term policy frameworks should be established for governments. For tunnel operators, a "high-frequency, small-step" incentive strategy should be employed.

(3) Reward and punishment mechanisms are effective tools for incentivizing tunnel operators, and thus governments should design them judiciously. Specifically, government subsidies (L) are not the primary factor influencing tunnel operators' decisions, and their value should be kept reasonably. Excessively high subsidies not only diminish the government's willingness to provide positive incentives but also prove counterproductive in encouraging operators to adopt low-carbon technologies. Regarding fines (F), a fine that is too low fails to provide sufficient impetus for both players to adopt positive carbon reduction strategies. Conversely, an excessively high fine will prolong the time required to achieve evolutionary equilibrium, also proving counterproductive.

(4) Lower adoption costs (P) and higher efficiency gains (G) for low-carbon technologies will incentivize tunnel operators to implement these measures. While pursuing maximum efficiency gains, operators must also prioritize cost control. Furthermore, the development and adoption of these technologies will drive down usage costs, while the increasing benefits of carbon emission reduction will bolster investor confidence. This dynamic can ultimately foster a self-sustaining green development paradigm.

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