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Research article

Tripartite evolutionary game analysis of cold chain logistics enterprises, NEV manufacturers, and government under dual-policy interventions

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Abstract: Cold chain logistics is an important source of carbon emissions, yet high investment costs often weaken enterprises' motivation for low-carbon transformation. This study constructs an evolutionary game model involving the government, cold chain logistics enterprises (CCLEs), and new energy vehicle manufacturers (NEVMs) under policy intervention. Using parameter values derived from industry statistics, we employed numerical simulations to analyze the stability of stakeholders' strategies and the system's equilibrium points. The results revealed that stakeholders' decisions are mutually dependent, while carbon tax penalties and environmental external costs serve as key drivers of low-carbon innovation. In particular, government subsidies can effectively accelerate NEV adoption, but excessive reliance on subsidies without penalties may hinder long-term stability. These findings provide managerial insights for designing balanced subsidy–penalty mechanisms in the cold chain logistics sector.

Keywords: cold chain logistics; carbon tax policy; tripartite evolutionary game; two-sided intervention policies

Mathematics Subject Classification: Primary: 90B06; Secondary: 91A35

1. Introduction

The cold chain constitutes a significant source of carbon emissions within the logistics sector, which plays an indispensable role in ensuring food safety, supporting communities, and safeguarding public welfare [1]. Due to the unique handling requirements of temperature-sensitive goods during transit and storage, cold chain operations generate a carbon footprint that distinguishes them from conventional logistics [2]. Refrigerated vehicles, for instance, are responsible for a staggering 96% of total greenhouse gas emissions during transportation, posing a considerable environmental threat [3]. It is evident that the environmental problems caused by cold chain logistics operation cannot be ignored. Under the “dual carbon” targets, enterprises should integrate sustainable development principles into all aspects of cold chain operations and actively pursue low-carbon transformation, including low-carbon transportation, emission reduction in storage, and energy-saving and environmental protection measures [4]. Accordingly, low-carbon transformation is viewed as crucial for the sustainable development of cold chain logistics enterprises (CCLEs).

In recent years, the government in China has implemented various strategies to reduce carbon emissions in the cold chain logistics sector. This includes the promotion of new energy vehicles, especially refrigerated trucks, which are considered effective in tackling carbon emissions and environmental pollution [5]. By 2023, China’s NEV industry had achieved remarkable growth, with production and sales reaching 10.54 million and 10.46 million units, respectively. However, the NEV industry still faces policy uncertainty [6], subsidy fluctuations [7], technological barriers [8], and market competition pressures [9]. These challenges have resulted in a relatively low adoption rate of NEVs among CCLEs, at approximately 5.32%.

Considering that the cold chain logistics supply chain involves multiple stakeholders—including the government, NEV manufacturers (NEVMs), and CCLEs—their effective interaction and cooperation are crucial to ensuring the authenticity and effectiveness of low-carbon development in this sector. The government can facilitate the development of NEVs through policy incentives and regulatory frameworks, thereby achieving both economic and environmental benefits. Meanwhile, decisions regarding NEV adoption must account for market dynamics, regulatory adjustments, and operational costs, allowing enterprises to respond flexibly to evolving market conditions. Therefore, an effective governance mechanism is urgently needed. It should balance environmental goals and economic efficiency while fostering coordination among stakeholders.

Although the importance of low-carbon operations in the cold chain logistics sector has been increasingly recognized, limited research has examined the dynamic interactions among stakeholders involved in NEV adoption. To fill this gap, this study explores the evolutionary processes of stakeholders’ low-carbon transformation and technological innovation behaviors under different market conditions and regulatory environments. By developing a tripartite evolutionary game model that includes CCLEs, NEVMs, and the government, this research captures the complex strategic relationships among these actors and provides theoretical insights for promoting coordinated low-carbon development in the cold chain logistics industry.

To address these issues, we investigate three key questions using both theoretical and empirical methods: (1) How do government subsidies and penalties influence the decision-making and dynamic interactions among stakeholders? (2) Should the government adopt stricter regulatory measures? Is it necessary to impose additional penalties on NEVMs for engaging in negative innovation behaviors? (3) How should CCLEs, the government, and NEVMs modify behavioral strategies in complex markets to achieve stability? We employ a tripartite evolutionary game model to analyze the strategic interactions among NEVMs, the government, and CCLEs. Based on Lyapunov’s first theorem, we derive evolutionarily stable strategy (ESS) conditions and conduct a sensitivity analysis to evaluate the influence of key factors on the evolution of optimal strategies.

The contribution of this research is threefold. First, this study applies an evolutionary game-theoretic framework to explore how policy interventions and market incentives influence the carbon-reduction strategies of cold chain logistics enterprises. Grounded in the principle of bounded rationality, which aligns with real-world decision-making in complex environments [10], this framework overcomes the limitations of conventional bilateral models. It not only uncovers novel evolutionary paths and stability conditions that such models cannot capture but also elucidates indirect governmental influence mechanisms. By analyzing the complex interactions among firms, government, and market stakeholders, this research provides a more holistic and integrated theoretical perspective on the sector's sustainable development. Second, unlike previous studies that focus solely on a single environmental policy [11], we examine a dual-policy intervention by the government, analyzing how the trade-off between subsidies and carbon tax penalties shapes stakeholders' decision-making pathways. Finally, the study provides practical policy implications for promoting low-carbon transformation in the cold chain logistics industry, offering guidance for designing balanced and effective policy mechanisms that coordinate government, enterprises, and new energy vehicle manufacturers.

The remaining sections of this paper are organized as follows: Section 2 presents a review of the relevant literature. Section 3 thoroughly discusses the game mechanism, fundamental model assumptions, and the stages involved in developing the tripartite evolutionary game model. In Section 4, we analyze the strategic decisions of each stakeholder within this framework. Section 5 presents numerical simulations conducted using MATLAB. Finally, Section 6 concludes the paper by summarizing the results and offering managerial recommendations.

2. Literature review

The article belongs to the body of research examining carbon emission reduction and government regulatory measures in cold chain logistics.

2.1. Carbon reduction strategies in cold chain logistics

Numerous studies have investigated carbon reduction strategies through optimization models in cold chain logistics. Zhang et al. [12] used a decision-making model for cold chain logistics systems. Qin et al. [13] developed a comprehensive vehicle routing optimization model aimed at minimizing the cost per satisfied customer. Liu et al. [14] employed a game-theoretic approach to analyze how supplier-retailer interactions influence R&D investments in carbon reduction technologies. Wei et al. [15] explored the relationship between demand uncertainty, government green subsidy design, and supplier profitability. By using a mixed-integer linear formulation, Giraldo et al. [16] compared a baseline scenario without taxation to a scenario explicitly incorporating carbon taxes. Widianingsih [17] used panel data from 47 countries to examine the effects of carbon taxes on emissions, highlighting the vital role of renewable energy in emission reduction. Planelles and Sanin [18] analyzed carbon taxation within global production networks and found that it helps mitigate the European Union's competitiveness losses caused by carbon pricing.

The effects of various environmental regulatory policies on corporate carbon emissions also differ. Cheng et al. [19] analyzed the impacts of various environmental regulations on emission reductions and technological advancements. Abbasi and Choukolaei [20] investigated the long-term effects of carbon regulations on the green supply chain over a decade. Recent studies have also focused on how government policies influence the adoption of low-carbon technologies by firms. Wu et al. [1] examined the overall effect of carbon taxes, innovation subsidies, and penalties on the adoption of low-carbon technology in addition to the effects of individual policies.

Other research questions in cold chain logistics have been explored, including supply chain network design [21,22], carbon footprint [23], truck routing problem [24–26], and supply chain coordination [27]. However, previous studies have focused on strategy-oriented analyses of carbon emission reduction, while overlooking the fact that stakeholders' decisions may evolve over time. Consequently, the long-term strategic decision-making behavior of players in the cold chain logistics system remains underexplored.

2.2. Promotion of new energy vehicles

Many studies on the new energy vehicle industry have been conducted from the perspectives of supply chain management, consumer preferences, and environmental impact.

From the perspective of supply chain management, several studies have explored topics such as policy-driven production and pricing decisions [28], government subsidy choices [29], and life-cycle emissions accounting [30, 31]. Shao and Jin [32] employed system dynamics modeling to evaluate supply chain resilience, identifying price, supply, and demand mechanisms as key factors for enhancing lithium supply chain resilience. Li et al. [33] analyzed the supply chain effects of dual credit and subsidy policies, specifically in relation to the NEV supply chain system. Cai et al. [34] studied a two-tier supply chain model, involving an NEV-sharing platform and an OEM under conditions of demand uncertainty. Xue et al. [35] used data from Chinese new energy vehicle firms and applied a difference-in-differences model to examine how promotion strategies influence firms' green technology development.

From a macro perspective, many scholars have focused on areas such as reverse logistics for end-of-life batteries, environmental performance assessment, and technological progress in battery energy storage systems. Franzò and Nasca [36] established a detailed evaluation framework to assess the environmental impact of electric vehicles and internal combustion engine vehicles through life cycle assessment. Su et al. [37] used a rolling-window Granger causality test to examine the environmental benefits of new energy vehicles and highlighted the role of the transportation sector in reducing air pollution. Wu et al. [38] employed web crawling and text mining techniques to analyze public opinions and attitudes toward NEVMs.

Although the literature on new energy vehicles within supply chain management is relatively extensive, research specifically addressing cold chain logistics remains limited. Hence, the potential contribution of NEVMs to improving low-carbon operational efficiency in cold chain logistics deserves more in-depth scholarly attention.

2.3. The application of game theory to corporate carbon reduction

Game theory has emerged as a vital strategy for addressing the challenge of corporate carbon emissions reduction. Wei et al. [15] developed a complex network-based evolutionary game model to study how environmental regulations affect the spread of low-carbon technologies. Xu et al. [39] investigated the impact of carbon policies on manufacturers' emission reduction investment decisions using a Stackelberg model. However, traditional game-theoretic approaches are often based on linear supply chains and tend to overlook the evolution of strategies in response to changing market environments.

Some scholars have increasingly employed evolutionary game models to examine stakeholders' decision-making behaviors regarding corporate carbon reduction. The evolutionary game approach, integrating elements of traditional game theory with dynamic adjustment processes, is increasingly used in fields such as economics, environmental management, and logistics. It provides a useful framework for exploring how strategic behaviors evolve over time, capturing the adaptive characteristics of organizational decision-making [40]. Zu et al. [41] examined a two-tiered supply chain that included a supplier and a manufacturer, exploring how CO_2 emission reduction could enhance profits under three environmental regulation scenarios. Zhang et al. [42] used an evolutionary game approach to evaluate the role of central environmental protection inspections in promoting carbon emission reduction. Wu et al. [1] developed an evolutionary game model involving the government, cold chain logistics enterprises, and financial institutions. Gao et al. [43] investigated mechanisms for governing greenwashing within the ESG framework of the NEV supply chain. Few studies employed a three-party evolutionary game model to examine the impacts of NEVMs, CCLEs, and government actions on carbon reduction behaviors.

2.4. Research gap

From the literature review, some research gaps can be identified. First, although extensive studies have examined cold chain logistics management through both empirical analyses and analytical models, most have focused on cold chain logistics enterprises, government agencies, and financial institutions, while overlooking the role of NEVMs.

Second, prior research has typically investigated binary supply chain structures under the assumption that players always make fully rational choices. In reality, however, stakeholders' decisions evolve over time [11, 44]. This highlights the need to analyze short-term instabilities while also capturing the long-term behavioral dynamics of players. To address this issue, the present study develops an evolutionary game model to investigate stakeholders' low-carbon operational strategies under government subsidies and environmental regulation.

Finally, much of the existing literature has concentrated on single environmental policies, such as subsidies, cap-and-trade schemes, or carbon tax policies. In practice, however, enterprises' decisions are simultaneously influenced by both subsidies and carbon penalties. To fill this gap, this study proposes a comprehensive framework for analyzing the strategic interactions of low-carbon operation stakeholders in cold chain logistics under dual-policy interventions. Table 1 summarizes the main distinctions between this study and the most closely related works.

Table 1. Comparison with literature.

Paper	Evolutionary game theory	NEV manufacturers	Environmental regulations	Cold chain logistics
Wu et al. [1]	√	×	√	×
Kang and Tan [11]	√	×	√	√
Gao et al. [43]	√	√	√	×
Wang et al. [45]	√	√	√	×
Zhao et al. [46]	√	×	√	√
This paper	√	√	√	√

3. Model introduction

3.1. Game mechanism

In this study, we examine the strategic interactions within CCLEs, the government, and NEVMs in the context of low-carbon coordinated development using a tripartite evolutionary game theory framework. Cold chain logistics serve as the cornerstone of low-carbon operations [1, 47]. On one hand, advancements in cold chain technology have improved logistics efficiency while reducing costs, creating favorable conditions for firms to achieve a low-carbon transition. On the other hand, advances in cold chain technology have reduced expenses and increased logistics efficiency, making it easier for firms to make the transition to a low-carbon economy. However, there are plenty of challenges that cold chain logistics must overcome, including high energy usage, costly equipment repair, and greenhouse gas emissions. These challenges not only increase the operational pressure on companies but also pose potential threats to environmental protection goals. Therefore, striking a balance between efficient operations and low-carbon development in cold chain logistics has become a critical issue.

In this process, market mechanisms and endogenous cooperation motives play a crucial role. For instance, long-term contracts can lower transaction risks and help maintain stable partnerships [1]; green brand premiums can increase consumer recognition and encourage firms to adopt low-carbon practices [48]; and supply chain synergy effect can promote resource sharing and cost savings, thereby strengthening the overall outcomes of coordinated development [49].

In addition, the government supports the low-carbon transformation of CCLEs through environmental reward and punishment policies, while the interaction between NEVMs and CCLEs must be strengthened not only under the guidance of external regulations but also through market-oriented incentives and endogenous drivers, ensuring policy compliance.

3.2. Basic assumptions

We propose the following hypotheses for the purpose of constructing a tripartite game model that involves the government, NEVMs, and CCLEs.

Hypothesis 1: The first subject is CCLEs, the second subject is NEVMs, and the third subject is the government. All three subjects are boundedly rational participants, and their strategy choices evolve over time to gradually stabilize at the optimal strategy.

Hypothesis 2: The strategy of CCLEs is $\alpha = (\alpha_1, \alpha_2) = (\text{transformation}, \text{no transformation})$. The strategy of NEVMs is $\beta = (\beta_1, \beta_2) = (\text{active innovation}, \text{negative innovation})$, and the probability of choosing β_1 is y, while the probability of choosing β_2 is $1 - y$, $y \in (0, 1)$. The government's strategy is $\gamma = (\gamma_1, \gamma_2) = (\text{regulation}, \text{no regulation})$, and the probability of choosing γ_1 is z, while the probability of choosing γ_2 is $1 - z$, $z \in (0, 1)$.

Hypothesis 3: The daily revenue of CCLEs is denoted as R_c. The cost of adopting low-carbon transformation is C_l, and the cost without transformation is C_0, where $C_l > C_0$. If CCLEs do not adopt a low-carbon transformation, higher carbon emissions or pollution occur. Consequently, the CCLEs may require NEVMs to accelerate technological innovation, which results in environmental external costs, denoted as B_t, where $B_t < (C_l - C_0)$. Here, B_t represents the uninternalized social cost caused by higher emissions, while C_p reflects the part of this cost internalized through policy instruments. This assumption reflects empirical patterns where the short-term costs of low-carbon adoption typically exceed the immediate social costs of emissions [48], thereby justifying a focus on the strategic interplay between CCLEs and NEVMs. Furthermore, CCLEs will incur a carbon tax penalty C_p, due to their high carbon emissions. For instance, they may need to purchase additional carbon allowances in the carbon trading market, directly raising operational costs. Therefore, C_p can be viewed as the policy-induced portion of the broader external cost B_t, capturing the government's attempt to internalize environmental damage.

Hypothesis 4: The daily revenue of NEVMs is denoted as P_t, derived from vehicle sales and related services. This revenue is influenced by market demand, technological innovation, and competition. However, negative innovation—resulting from excessive investment, misaligned direction, or inaccurate market demand forecasts—can lead to additional costs C_t, including R&D expenses, production complexities, and inventory holding costs.

Hypothesis 5: When the government imposes strict regulations, CCLEs that fail to adopt low-carbon transformation face a carbon tax penalty F_y, which further strengthens the constraint effect of the basic carbon tax C_p under stringent regulatory conditions. Meanwhile, NEVMs engaging in negative innovation incur fines F_t. On the other hand, CCLEs adopting low-carbon transformation receive a subsidy M_p, and NEVMs involved in active innovation receive a subsidy M_t. Strict regulations incur significant human and financial costs, denoted as C_g. However, in the case of loose regulations, no rewards or penalties are imposed on the enterprises.

Hypothesis 6: When CCLEs implement low-carbon transformation, the government gains social stability, economic growth, and authenticity, contributing to social benefits W_g. If CCLEs do not adopt low-carbon transformation and NEVMs engage in negative innovation, the government incurs environmental governance costs D_g. Additionally, if the government adopts loose regulation, environmental degradation costs T_g will arise.

Based on the hypotheses mentioned above, Table 2 presents the symbols and meanings of the parameters used in this paper.

Table 2. Symbols and definition

Symbol	Definition
R_c	Daily revenue of CCLEs
C_l, C_0	Costs associated with low-carbon transformation (C_l) and non-low-carbon transformation (C_0), where $C_l > C_0$
C_t	Cost of active innovation for NEVMs
C_g	Cost of strict environmental regulation
C_p	Carbon tax for CCLEs that do not adopt low-carbon transformation
B_t	Environmental external cost
P_t	Daily revenue of NEVMs
M_p, M_t	Government subsidies: M_p for low-carbon transformation of CCLEs and M_t for active innovation of NEVMs
F_p, F_t	Carbon tax penalties: F_p for non-low-carbon transformation of CCLEs and F_t for negative innovation of NEVMs
W_g	Social benefits
D_g	Environmental governance costs for CCLEs that do not adopt low-carbon transformation
T_g	Environmental degradation costs caused by loose regulation, $T_g > C_g$

3.3. Payment matrix

Based on the model assumptions and parameters, we constructed a mixed-strategy game matrix for CCLEs, the government, and NEVMs, as shown in Table 3.

Table 3. Mixed strategy benefit matrix

CCLEs	NEVMs	Government	Strict regulation (z)	Loose regulation ($1-z$)
Low-carbon operation (x)	Active innovation (y)	CCLEs	$R_c - C_l + M_p$	$R_c - C_l$
		NEVMs	$P_t + M_t$	P_t
		Government	$-C_g - M_p - M_t + W_g$	W_g
	Negative innovation ($1-y$)	CCLEs	$R_c - C_l + M_p$	$R_c - C_l$
		NEVMs	$P_t - C_t - F_t$	$P_t - C_t$
		Government	$-C_g - M_p + F_t + W_g$	W_g
Low-carbon transformation ($1-x$)	Active innovation (y)	CCLEs	$-C_0 - C_p - F_p$	$-C_0 - C_p$
		NEVMs	$P_t + M_t$	P_t
		Government	$-C_g + F_p - M_t$	0
	Negative innovation ($1-y$)	CCLEs	$R_c - C_0 - C_p - B_t - F_p$	$R_c - C_0 - C_p - B_t$
		NEVMs	$P_t - C_t + B_t - F_t$	$P_t - C_t + B_t$
		Government	$-C_g + F_p + F_t - D_g$	$-D_g - T_g$

4. Model analysis

In this section, we conduct a detailed analysis of the model, focusing on the strategic stability of three players. This analysis will help us understand the behavior of the system and identify the key factors influencing stability.

4.1. Strategic stability analysis of CCLEs

The expected benefits of a low-carbon transformation, a non-low-carbon transformation, and dynamic equations for the strategy selection replication of CCLEs are as follows:

$$E_{11} = yz[R_c - C_l + M_p] + y(1-z)[R_c - C_l] + (1-y)z[R_c - C_l + M_p] + (1-y)(1-z)[R_c - C_l] \tag{4.1}$$

$$E_{12} = yz(-C_0 - C_p - F_p) + y(1-z)(-C_0 - C_p) + (1-y)z(R_c - C_0 - C_p - B_t - F_p) + (1-y)(1-z)(R_c - C_0 - C_p - B_t) \tag{4.2}$$

$$\overline{E_1} = xE_{11} + (1-x)E_{12} \tag{4.3}$$

Let $G(y) = (y-1)B_t + C_l - C_p - z(F_p + M_p) - R_c$, so $F(x) = x(E_{11} - \overline{E_1}) = x(x-1)G(y)$. Thus, we can get $\frac{dF(x)}{dx} = (1-2x)G(y)$. When $y = \frac{C_l - C_0 - C_p - B_t - z(F_p+M_p)}{R_c - B_t} = y^*$, $G(y) = 0$ and $F(x) = 0$, indicating an evolutionarily stable state for any value of x. Since $\frac{\partial G(y)}{\partial y} = B_t - R_c < 0$, $G(y)$ is a decreasing function.

$G(y)$ is a decreasing function. When $y < y^*$, $G(y) > 0$, $F'(x)|_{x=0} < 0$, where $x = 0$ represents the evolutionarily stable strategy (ESS) of CCLEs. Conversely, when $y > y^*$, $G(y) < 0$, and $F'(x)|_{x=1} < 0$, where $x = 1$ is the ESS. The phase diagram of dynamic evolutionary trends is shown in Figure 1.

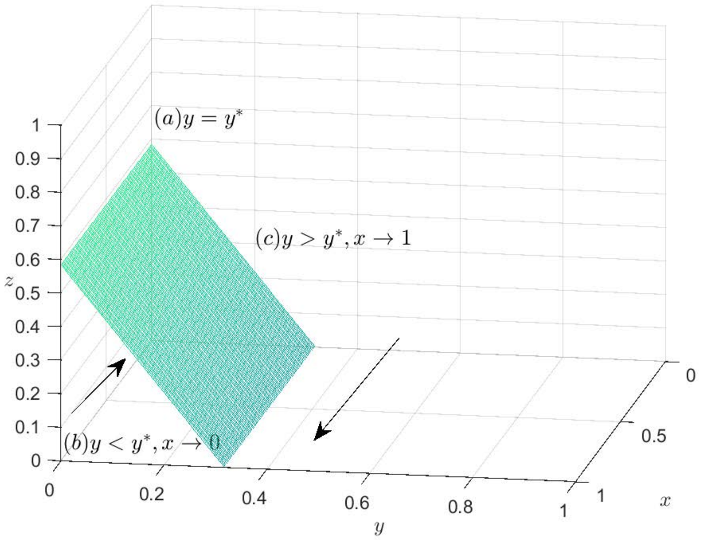


Figure 1. Dynamic evolution trend of CCLEs.

The volume V_{X_0} of X_0 shows the probability that CCLEs will choose low-carbon transformation, while the volume V_{X_1} of X_1 indicates the likelihood that they will not. This is demonstrated in Figure 1.

$$V_{X_0} = \int_0^1 \int_0^1 \frac{C_l - C_0 - C_p - B_t - z(F_p + M_p)}{R_c - B_t} dzdx = \frac{B_t + C_0 - C_l + C_p + \frac{F_p + M_p}{2}}{B_t - R_c} \tag{4.4}$$

$$V_{X_1} = 1 - V_{X_0} \tag{4.5}$$

Inference 1. The probability of low-carbon transformation for CCLEs is positively related with daily revenue, carbon taxes, environmental external cost, and government subsidies and penalties. However, it is negatively related with the costs associated with low-carbon transformation.

Proof. Calculate each element's first-order partial derivatives for V_{X_1} to obtain the following: $\frac{\partial V_{X_1}}{\partial R_c} > 0$, $\frac{\partial V_{X_1}}{\partial C_p} > 0$, $\frac{\partial V_{X_1}}{\partial B_t} > 0$, $\frac{\partial V_{X_1}}{\partial F_p} > 0$, $\frac{\partial V_{X_1}}{\partial M_p} > 0$, and $\frac{\partial V_{X_1}}{\partial C_l} < 0$. Thus, when R_c, C_p, B_t, F_p, M_p increase or C_l increases, both can increase the probability that CCLEs will decide to achieve low-carbon transformation.

4.2. Strategic stability analysis of NEVMs

The following are the replication dynamic equations for the expected benefits of negative innovation, active technical innovation, and strategy selection:

$$E_{21} = xz(P_t + M_t) + x(1 - z)P_t + (1 - x)z(P_t + M_t) + (1 - x)(1 - z)P_t \tag{4.6}$$

$$\begin{aligned} E_{22} = {} & xz(P_t - C_t - F_t) + x(1 - z)(P_t - C_t) \\ & + (1 - x)\left[z(P_t - C_t + B_t - F_t) + (1 - z)(P_t - C_t + B_t)\right] \end{aligned} \tag{4.7}$$

$$\overline{E_2} = yE_{21} + (1 - y)E_{22} \tag{4.8}$$

Let $G(z) = C_t + (x - 1)B_t + z(F_t + M_t)$, then $F(y) = \frac{dy}{dt} = y(E_{21} - \overline{E_2}) = y(1 - y)G(z)$, so we can obtain $\frac{dF(y)}{dy} = (1 - 2y)G(z)$. During $z = \frac{(1-x)B_t - C_t}{F_t + M_t} = z^*$, $G(z) = 0$ and $F(y) = 0$, so all values of y are in an evolutionarily stable state. Additionally, since $\frac{\partial G(z)}{\partial z} < 0$, $G(z)$ is a decreasing function. Therefore, when $z < z^*$, $G(z) > 0$, $F'(y)|_{y=0} < 0$, where $y = 0$ represents the ESS of NEVMs. Conversely, when $z > z^*$, $G(z) < 0$, $F'(y)|_{y=0} > 0$, where $y = 1$ is the ESS.

Figure 2 displays a phase diagram illustrating the strategic evolution of the NEVMs. Hence, Equation (10) is used to calculate the volume V_{Y_0} of the probability Y_0 of NEVMs:

$$V_{Y_0} = \int_0^1 \int_0^1 \frac{(1 - x)B_t - C_t}{F_t + M_t} dxdy = \frac{(C_t - B_t)^2}{2B_t(F_t + M_t)} \tag{4.9}$$

$$V_{Y_1} = 1 - \frac{(C_t - B_t)^2}{2B_t(F_t + M_t)} \tag{4.10}$$

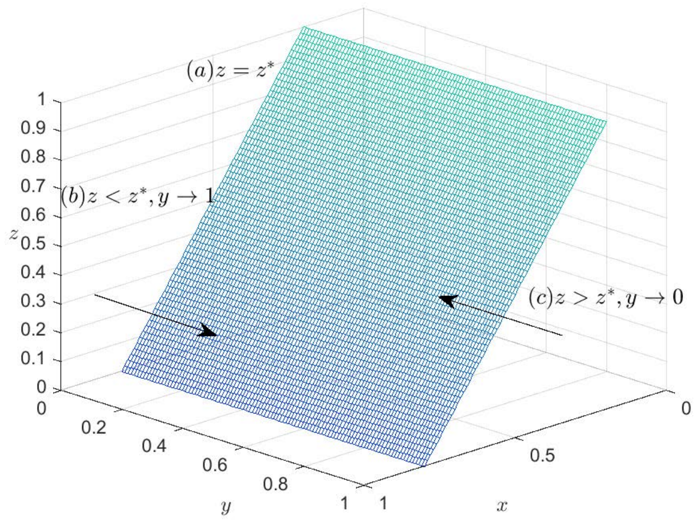


Figure 2. Dynamic evolution trend of NEVMs.

Inference 2. The probability of active technological innovation for NEVMs is negatively correlated with increased environmental external costs, subsidies for low-carbon transformation, and non-low-carbon transformation fines, and positively correlated with active innovation costs.

Proof. Calculate V_{Y_1}'s first-order partial derivatives with respect to each element, and thus we obtain: $\frac{\partial V_{Y_1}}{\partial B_t} < 0$, $\frac{\partial V_{Y_1}}{\partial M_t} < 0$, $\frac{\partial V_{Y_1}}{\partial F_t} < 0$, $\frac{\partial V_{Y_1}}{\partial C_t} > 0$.

4.3. Strategic stability analysis of the government

The replication dynamic equations for the expected benefits of strict and loose regulation by the government and the strategy selection are as follows:

$$\begin{aligned} E_{31} = {} & xy(-C_g - M_p - M_t + W_g) + x(1-y)(-C_g - M_p + F_t + W_g) \\ & + (1-x)y(-C_g + F_p - M_t) + (1-x)(1-y)(-C_g + F_p + F_t - D_g) \end{aligned} \tag{4.11}$$

$$E_{32} = xyW_g + x(1-y)W_g + 0 + (1-x)(1-y)(-D_g - T_g) \tag{4.12}$$

$$\overline{E_3} = zE_{31} + (1-z)E_{32} \tag{4.13}$$

Let $G(y) = C_g - F_t - T_g + F_p(x-1) + (M_p + T_g)x + (F_t + M_t + T_g - T_g x)y$, then $F(z) = \frac{dz}{dt} = z(E_{31} - \overline{E_3}) = z(z-1)G(y)$. So, we have $\frac{dF(z)}{dz} = (1-2z)G(y)$. During $y = \frac{-C_g+F_p+F_t+T_g-(F_p+M_p+T_g)x}{F_t+M_t+T_g(1-x)} = y^*$, $G(y) = 0$, and $F(z) = 0$, then all values of z are in an evolutionarily stable state. Since $\frac{\partial G(y)}{\partial y} > 0$, $G(y)$ is an increasing function of y. When $y < y^*$, $G(y) < 0$, $F'(z)|_{z=1} < 0$; hence, $z = 1$ represents government's ESS, while when $y > y^*$, $z = 0$ is the ESS.

In Figure 3, the volume of probability V_{Z_1} for loose regulation is $V_{Z_1} = 1 - V_{Z_0}$, while the value of likelihood Z_0 for the government to regulate is V_{Z_0}. Hence, the calculation is shown as follows:

$$\begin{aligned} V_{Z_0} &= \int_0^1 \int_0^1 \frac{-C_g + F_p + F_t + T_g - (F_p + M_p + T_g)x}{F_t + M_t + T_g(1-x)} dxdz \\ &= \ln\left(\frac{F_t + M_t + T_g}{F_t + M_t}\right)\left(-C_g + F_p + F_t + T_g - \frac{F_p + M_p + T_g}{2}\right) \end{aligned} \tag{4.14}$$

$$V_{Z_1} = 1 - \ln\left(\frac{F_t + M_t + T_g}{F_t + M_t}\right)\left(-C_g + F_p + F_t + T_g - \frac{F_p + M_p + T_g}{2}\right) \tag{4.15}$$

Inference 3. The probability of active innovation for NEVMs is negatively correlated with increased environmental external costs, subsidies for low-carbon transformation, and non-low-carbon transformation fines, and positively correlated with active innovation costs.

Proof: Calculate V_{Z_0}'s first-order partial derivatives with respect to each element, and thus we obtain: $\frac{\partial V_{Z_0}}{\partial F_t} > 0$, $\frac{\partial V_{Z_0}}{\partial F_p} > 0$, $\frac{\partial V_{Z_0}}{\partial T_g} > 0$, $\frac{\partial V_{Z_0}}{\partial M_t} < 0$, $\frac{\partial V_{Z_0}}{\partial M_p} < 0$.

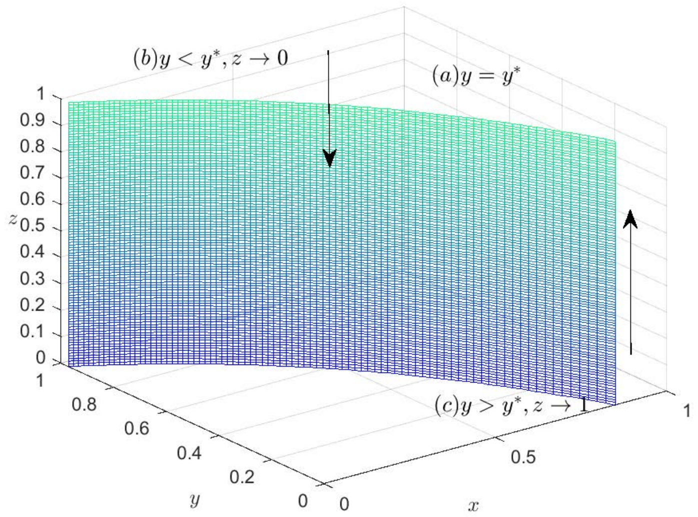


Figure 3. Dynamic evolution trend of NEVMs.

4.4. Analysis of equilibrium points in tripartite evolutionary game systems for strategic stability

In this subsection, we conducted an extensive analysis of the three-party system based on the strategic stability of the government, NEVMs, and CCLEs. The system equilibrium points can be obtained from $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$:

$$
\begin{gathered}
E_1(0,0,0),\ E_2(1,0,0),\ E_3(0,1,0),\ E_4(0,0,1),\ E_5(1,1,0),\\
E_6(1,0,1),\ E_7(0,1,1),\ E_8(1,1,1),\\
E_9\left(0, \frac{-C_g + F_p + F_t + T_g}{F_t + M_t + T_g}, \frac{B_t - C_t}{F_t + M_t}\right),\\
E_{10}\left(\frac{-C_g + F_p + F_t + T_g}{F_t + M_t + T_g}, 0, \frac{C_l - C_0 - C_p - B_t}{F_p + M_p}\right),\\
E_{11}\left(\frac{F_p - C_g - M_t}{F_p + M_p}, 1, \frac{C_l - C_0 - C_p - R_c}{F_p + M_p}\right),\\
E_{12}\left(1 - \frac{C_t}{B_t}, \frac{C_l - C_0 - C_p - B_t}{R_c - B_t}, 0\right),\\
E_{13}\left(\frac{B_t - M_t - (F_t + C_t)}{B_t}, \frac{C_l - C_0 - C_p - B_t - (F_p + M_p)}{R_c - B_t}, 1\right)
\end{gathered}
$$

Based on the hypothesis, it is known that $C_l - C_0 - C_p - R_c < 0$, thus E_{11} is meaningless. Meanwhile, since $x, y, z \in [0,1]$, E_9–E_{13} are meaningful. Thus, the Jacobian matrix of this game system is as follows:

$$
J = \begin{bmatrix}
(1-2x)(B_t - C_l + C_p + y(R_c - B_t) + (F_p + M_p)z) & x(x-1)(B_t - R_c) & x(1-x)(F_p + M_p) \\
y(1-y)B_t & (1-2y)(C_t + B_t(x-1) + (F_t + M_t)z) & y(1-y)(F_t + M_t) \\
z(z-1)(F_p + M_p + T_g(1-y)) & z(z-1)(F_t + M_t + T_g(1-x)) & (2z-1)G(x,y)
\end{bmatrix}
$$

Where $G(x, y) = (x-1)((1-y)T_g + F_p) + y(F_t + M_t) + xM_p + C_g - F_t$.

The first Lyapunov method is used to analyze the stability of equilibrium points in dynamical systems, with stability determined by the eigenvalues of the Jacobian matrix at the equilibrium point. If all eigenvalues have negative real parts, the equilibrium point is asymptotically stable; if at least one eigenvalue has a positive real part, the equilibrium point is unstable; and when some eigenvalues have zero real parts, while the others have negative real parts, the equilibrium point is in a critical state, and its stability cannot be conclusively determined from the eigenvalues alone.

In this study, the Jacobian matrices for equilibrium points from E_9 to E_{13} contain eigenvalues with different signs, indicating that these equilibrium points are unstable. In contrast, a more detailed stability analysis of the equilibrium points from E_1 to E_8 is presented in Table 4, which provides further insights into their stability characteristics.

Table 4. Stability analysis of equilibrium points.

Equilibrium	Eigenvalue	Symbol	Condition
$E_1(0,0,0)$	$C_t - B_t,\ B_t - C_l + C_p,\ F_g - C_g + F_t + T_g$	$(-,-,+)$	Instability
$E_2(1,0,0)$	$C_t,\ C_l - B_t - C_p,\ F_t - C_g - M_p$	$(+,+,\times)$	Instability
$E_3(0,1,0)$	$B_t - C_t,\ C_p - C_l + R_c,\ F_p - C_g - M_t$	$(+,+,\times)$	Instability
$E_4(0,0,1)$	$C_l - C_0 + C_p + B_t + F_p + M_p,\ C_t - B_t + F_t + M_t,\ C_g - F_p - F_t - T_g$	$(-,-,-)$	Instability
$E_5(1,1,0)$	$-C_t,\ -C_g - M_p - M_t,\ C_l - C_p - R_c$	$(-,-,-)$	ESS Condition 1
$E_6(1,0,1)$	$C_t + F_t + M_t,\ C_g - F_t + M_p,\ C_l - B_t - C_p - F_p - M_p$	$(+,\times,+)$	Condition 2
$E_7(0,1,1)$	$C_g - F_p + M_t,\ B_t - C_t - F_t - M_t,\ C_p - C_l + F_p + M_p + R_c$	$(+,\times,\times)$	Condition 3
$E_8(1,1,1)$	$C_g + M_p + M_t,\ -C_t - F_t - M_t,\ C_l - C_p - F_p - M_p - R_c$	$(-,-,+)$	Condition 4

The stability of the remaining five equilibrium points can be analyzed using the following four scenarios. When the conditions $M_p < -C_l + C_0 - C_p - B_t - F_p$, and $M_t < B_t - F_t - C_t$ are satisfied, the equilibrium points $E_4(0,0,1)$ and $E_5(1,1,0)$ become stable. These inequalities are collectively referred to as Condition 1. Condition 2 and Condition 3, related to government subsidies, are as follows: $F_t - C_g < M_p < C_l - B_t - C_p - F_p$, $B_t - C_t - F_t < M_t < F_p - C_g$. In addition, Condition 4, related to costs, is $C_l < C_p + F_p + M_p + R_c$.

5. Simulation analysis

5.1. Data sources and parameter description

In this section, model parameters are assigned based on proportional relationships derived from real-world cases and literature references. The values are set as follows: $R_c = 100$, representing the daily revenue estimate for cold-chain logistics enterprises [50, 51]; $C_l = 85$, reflecting the high costs from equipment upgrading, process innovation, and carbon capture associated with low-carbon transformation [52]; and $C_0 = 0$, corresponding to no additional investment without low-carbon transformation [53]. Additional parameters are set as $C_p = 10$, $B_t = 40$, $F_p = 40$, $M_p = 20$, $C_t = 10$, $F_t = 20$, $M_t = 15$, $C_g = 15$, and $T_g = 40$, which satisfy the conditions required for the stable point $E_5(1, 1, 0)$.

5.2. Impact of the initial intentions of the three parties

Figure 4 illustrates the evolutionary outcomes based on the above analysis. It shows that as the probability of CCLEs adopting a low-carbon transformation and NEVMs engaging in active innovation increases, the likelihood of the government enforcing strict regulation gradually declines to nearly zero. Thus, the final evolutionary outcome is $E_5(1, 1, 0)$, which is consistent with the above analysis.

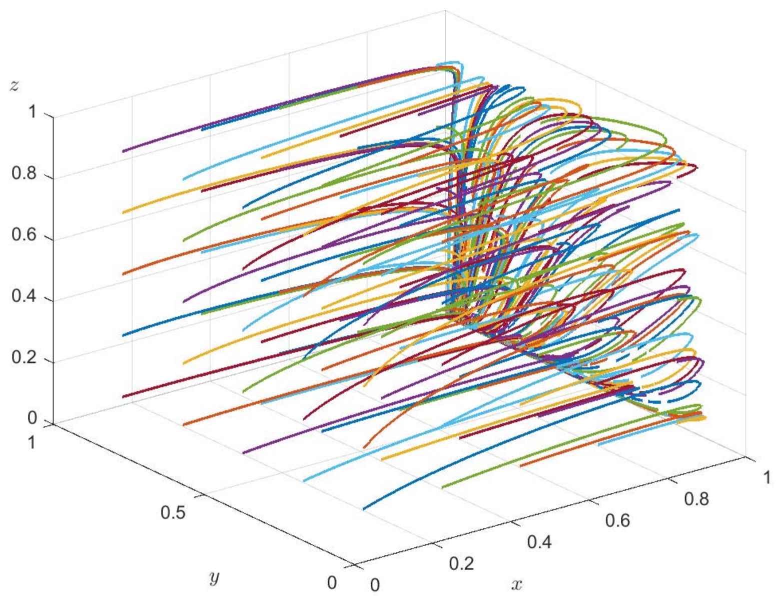


Figure 4. Evolutionary result.

Then, we analyzed the impact of initial intentions on the evolutionary process, as shown in Figure 5. The initial participation probabilities were set as $x = y = z = \{0.2, 0.5, 0.8\}$, with all other parameters held constant.

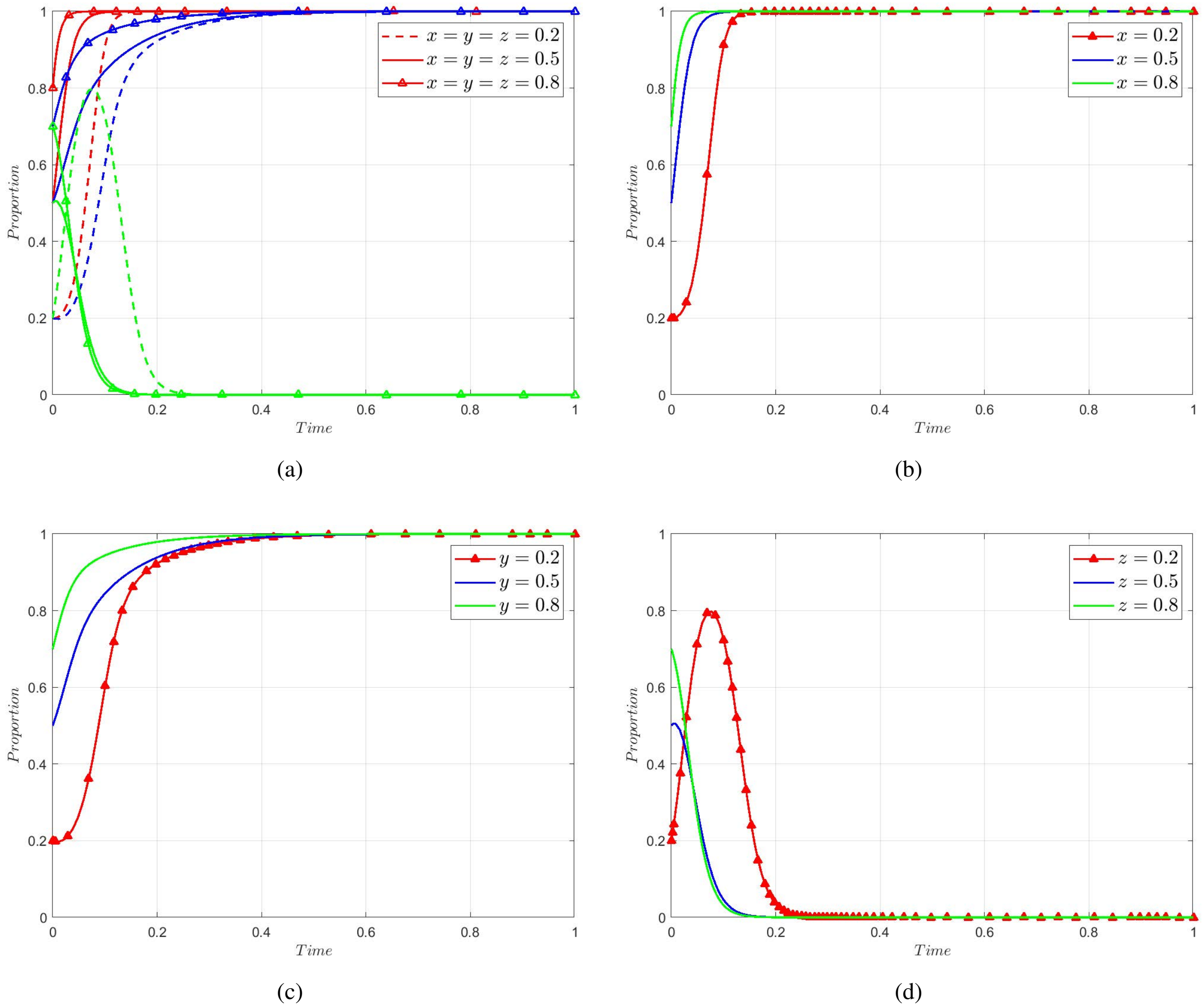


Figure 5. The effect of changes in the subject's initial willingness on the evolutionary outcome.

Figure 5(a) illustrates how variations in the initial willingness of the three subjects affect the evolutionary outcomes. As shown in Figure 5(a), when the initial willingness increases from 0.2 to 0.8, the strategies of all three subjects eventually converge to 1. Specifically, when the initial willingness of the government and CCLEs is relatively low, NEVMs exhibit a lower willingness to actively innovate during the initial stages. This is because technological innovation by NEVMs becomes highly challenging without government policy support and incentives from CCLEs. Conversely, when the initial willingness of all three subjects is high, the system quickly stabilizes in a short period, with a final cooperation rate nearing 1. This indicates that under high willingness conditions, the cooperative drive among the three subjects is exceptionally strong, forming an optimal state of collaboration.

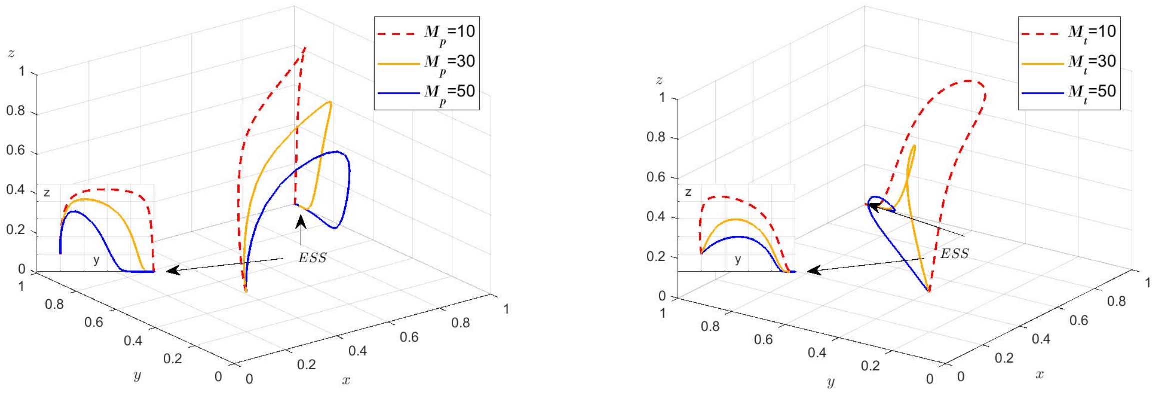
Figure 5(b), 5(c), and 5(d) illustrate the mutual influence of three subjects' initial willingness. Figures 5(b) and 5(c) indicate that NEVMs are more sensitive to the initial willingness of other subjects, whereas CCLEs are more strongly influenced by the government's initial willingness. As the initial willingness of the government and CCLEs to transform increases, adjustments to low-carbon transformation strategies are driven by the proactive innovation willingness of NEVMs. Notably,

Figure 5(d) reveals that when the government's initial willingness is low—indicating weak policy enforcement—its impact on the overall evolutionary process is limited. Overall, these results highlight the crucial role of each subject's willingness in shaping the ultimate evolutionary outcomes within the cold chain logistics industry.

5.3. Parameter change analysis

5.3.1. Impact of government subsidies and carbon tax penalties

In this subsection, we examine the impact of various government subsidies on the decision-making processes of CCLEs and NEVMs. Specifically, we introduce two key parameters: M_p, representing government subsidies aimed at supporting the low-carbon transformation of CCLEs, and M_t, denoting subsidies that encourage active innovation in NEVMs.



(a) (b)

Figure 6. The effect of M_p and M_t on the game equilibrium.

Figure 6(a) illustrates that as M_p increases from 10 to 50 (corresponding to approximately 12%–59% of C_l), the willingness of both CCLEs and NEVMs to adopt low-carbon strategies significantly improves. The system reaches a stable equilibrium at specific subsidy levels, where the optimal strategies of all stakeholders align. This indicates that moderate subsidies, corresponding to roughly 20%–40% of the low-carbon transformation cost, are sufficient to stimulate corporate participation while avoiding over-dependence on policy incentives.

Figure 6(b) shows the "spillover effect" of subsidies across the supply chain. Increases in M_t similarly accelerate NEVMs' innovation efforts, reinforcing collaborative behaviors among stakeholders. However, excessive subsidies beyond 50 ($\approx$ 59% of C_l) reduce autonomous decision-making, indicating that overly high financial incentives may weaken market-driven innovation. Overall, these results support the use of a balanced subsidy strategy, with moderate subsidies providing effective incentives while maintaining market autonomy.

Figures 7(a) and 7(b) illustrate the impact of F_p (carbon tax penalties for CCLEs) on the strategic decision-making dynamics of NEVMs and the government, respectively.

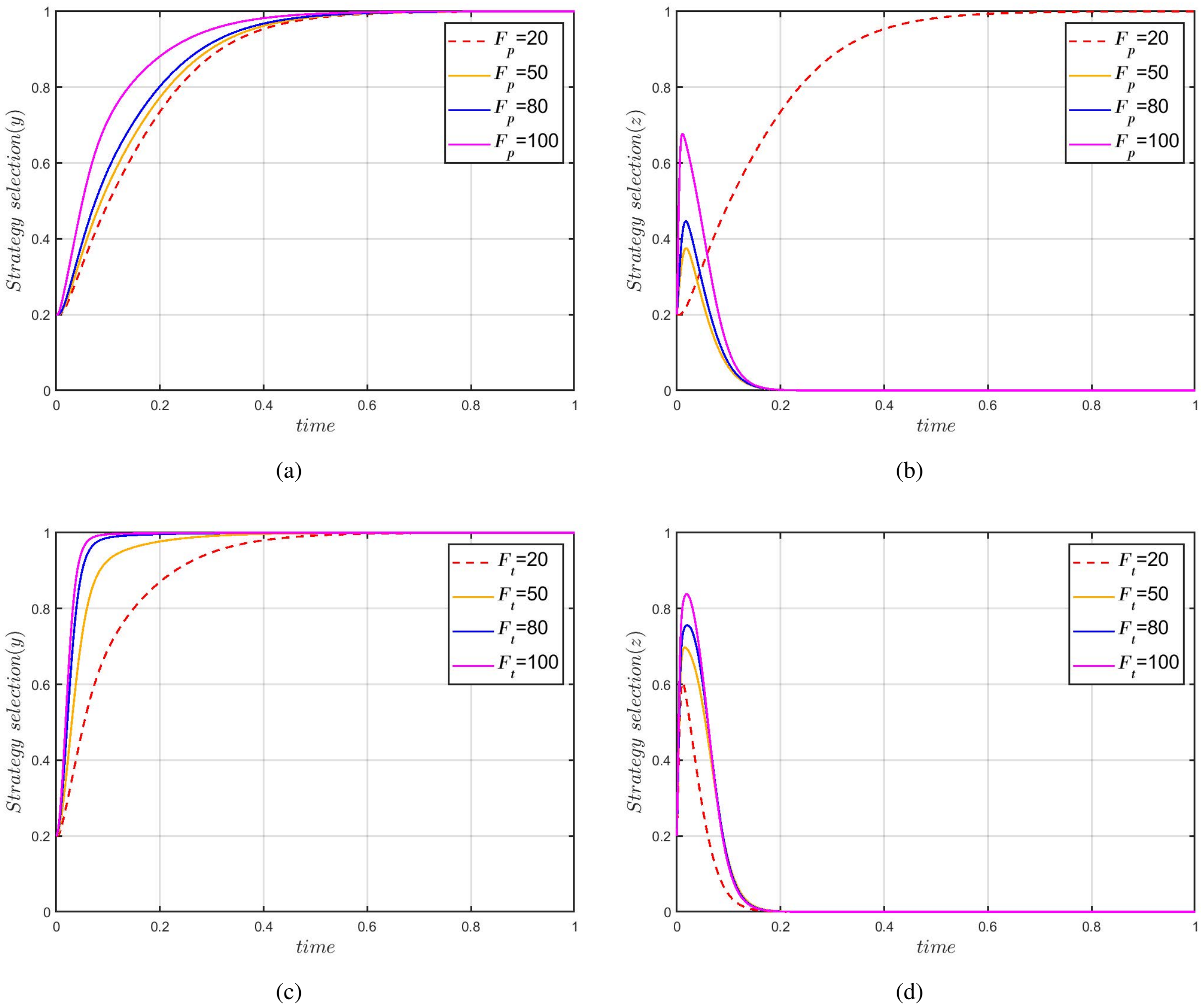


Figure 7. Evolution path of the system with different values of F_t and F_p.

From Figure 7(a), it is obvious that as F_p increases, the strategic response speed of NEVMs accelerates, and their final strategy values rise significantly. This indicates that higher carbon tax penalties effectively drive CCLEs to adopt low-carbon transition strategy. In contrast, Figure 7(b) shows that the initial intensity of government strategies strengthens with the increase in F_p, but the duration of their influence shortens, ultimately converging to zero. This implies that higher carbon tax penalties have a stronger short-term incentive effect on government strategies but serve as a more powerful long-term driver for CCLEs. Figures 7(c) and 7(d) illustrate how F_t (carbon tax penalties for NEVMs) affects the strategies of NEVMs and the government. As F_t increases, the initial response of NEVMs shows minimal variation, but their strategies stabilize more rapidly, and the final steady-state values rise. This indicates that higher carbon tax penalties can accelerate NEVMs' adaptation to environmental regulations and encourage more active innovation strategies in the long term.

5.3.2. Impact of enterprise revenue and environmental external cost

In this subsection, we analyze the impact of two key parameters, R_c (daily revenue of CCLEs) and B_t (environmental external cost), on the game equilibrium.

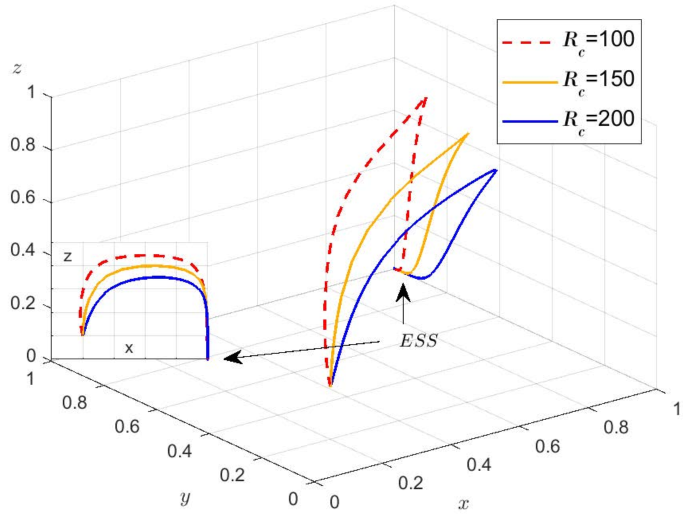
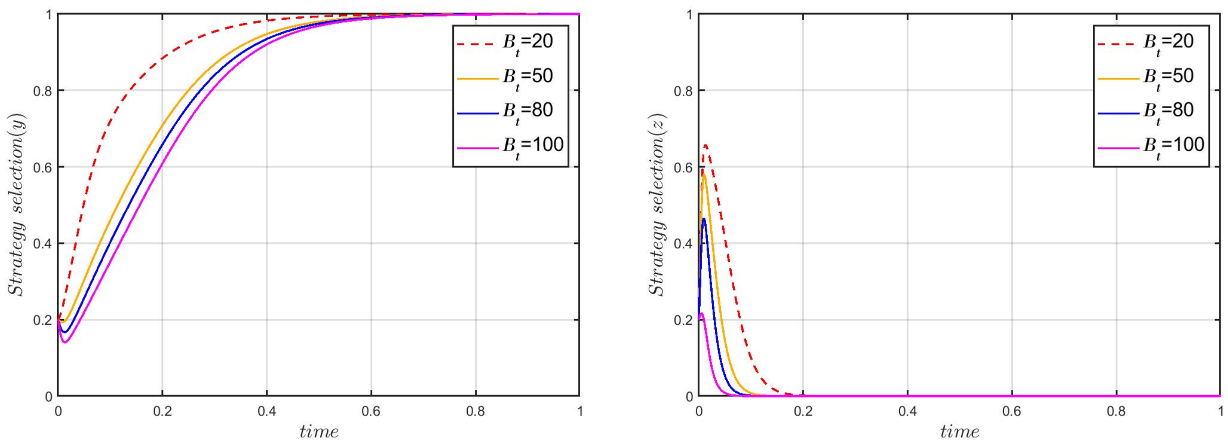


Figure 8. The effect of R_c on the game equilibrium.

Figure 8 illustrates the impact of R_c on the game equilibrium. From Figure 8, it can be seen that as R_c increases from 100 to 200, the changes do not alter the strategy choices of CCLEs, but they do affect the stability of their evolution. In other words, as R_c rises, the probability of CCLEs opting for low-carbon transformation increases, while the probability of the government imposing strict regulations decreases.



(a) (b)

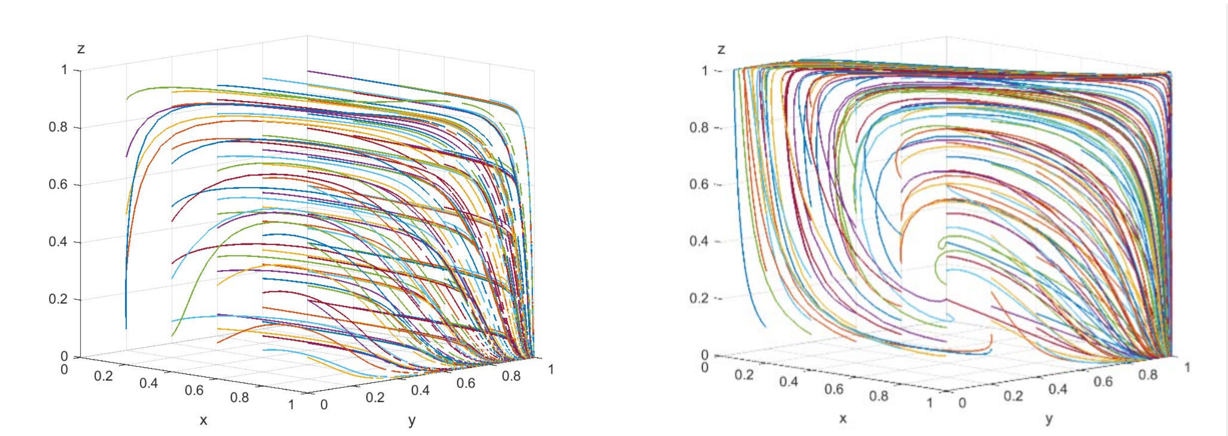
Figure 9. Evolution path of the system with different values of B_t.

Figure 9 illustrates the evolutionary paths of NEVMs and the government with varying values of B_t. From Figure 9(a), it can be seen that the environmental external cost significantly influences both the speed and pathway of strategy selection for NEVMs. The findings indicate that a lower external cost ($B_t = 20$) can substantially accelerate the decision-making process of NEVMs, leading to a quicker stabilization of the system. In contrast, a higher external cost ($B_t = 100$) slows down the strategy adjustment process. This is because elevated external costs not only intensify the environmental pressures on enterprises but may also compel them to reassess the balance between risks and benefits, thereby delaying the implementation of strategies.

Figure 9(b) illustrates the dynamic trend of the government's strategy choice with different values of environmental external costs B_t. As B_t increases, NEVMs tend to adopt more proactive innovation strategies. However, regardless of B_t, government intervention declines rapidly over time—starting with strong initial regulation that quickly weakens. Notably, when B_t is lower ($B_t = 20$), the government enforces stricter regulations, whereas a higher B_t ($B_t = 100$) leads to a more moderate initial intervention. This suggests that when environmental external costs are lower, the government tends to implement more stringent regulations.

5.3.3. Numerical simulation analysis of system evolution

Array (1) and (2) evolved 50 times, with each iteration starting from a different initial strategy combination, as shown in Figure 10. From Figure 10(a), it can be observed that $E_5(1, 1, 0)$ represents a stable equilibrium state. This indicates that, provided that the benefits of active innovation or low-carbon transformation are sufficiently high, CCLEs can pursue low-carbon transformation independently, without reliance on government subsidies. Conversely, when the societal benefits of government environmental regulations do not outweigh the associated regulatory costs, the government's inclination toward strict regulation diminishes. In such cases, the application of rewards or penalties to CCLEs may also decrease. This highlights the importance of balancing regulatory costs with societal benefits to effectively drive low-carbon transitions.



(a) Arrays (1) evolved 50 times

(b) Arrays (2) evolved 50 times

Figure 10. The evolutionary results of Arrays (1) and Arrays (2) over 50 generations.

The parameter values of array (2) are defined as follows: $R_c = 100$, $C_l = 100$, $C_0 = 5$, $C_p = 10$, $B_t = 50$, $F_p = 30$, $M_p = 20$, $C_t = 10$, $F_t = 20$, $M_t = 15$, $C_g = 15$, $T_g = 40$. Hence, the initial model parameters, represented by array (2), have evolved through 50 iterations under various strategy combinations, as illustrated in Figure 10(b). Figure 10(b) illustrates two stable states, $E_4(0, 0, 1)$ and $E_5(1, 1, 0)$, which correspond to two distinct scenarios: the outcomes of strict government regulation coupled with negative innovation without the low-carbon transformation, and loose government regulation alongside active innovation with low-carbon transformation. This indicates that strict regulation is an effective approach to promoting low-carbon transformation in CCLEs.

5.3.4. Summary and discussion

We have systematically synthesized the preceding numerical simulation results into a comprehensive analytical framework (see Table 5). This framework clarifies the strategic effects of key parameters on the tripartite evolutionary game. It explicitly indicates the sensitivity of each stakeholder's strategy to these parameters—using (+) for a positive correlation and (−) for a negative correlation.

Table 5. Effect of key parameters on stakeholder strategies.

Key parameter	Effect on CCLEs' strategy	Effect on NEVMs' strategy	Effect on government's strategy
Government subsidies (M_p, M_t)	(+)	(+)	(−)
Carbon tax penalties (F_p, F_t)	(+)	(+)	Mixed (increases initial intensity but shortens duration)
Enterprise revenue R_c	(+)	No significant direct impact analyzed	(−)
External cost B_t	No significant direct impact analyzed	(−)	(−)

Table 5 synthesizes the strategic impact of key parameters on the stakeholders' evolutionary paths. The analysis reveals that subsidies and penalties function as distinct "pull" and "push" mechanisms, respectively; both effectively encourage proactive strategies from CCLEs and NEVMs, but they inversely affect the necessity and duration of government regulation. Furthermore, firm-level characteristics are critical drivers. Higher enterprise revenue fosters voluntary transformation, reducing the government's regulatory burden. Conversely, higher external costs introduce a cautionary dynamic, slowing innovation and moderating initial government intervention. Overall, these findings underscore the complex interplay between direct policy incentives, enterprise capacity, and risk considerations in shaping the system's trajectory toward a sustainable equilibrium.

6. Conclusions and management implications

6.1. Conclusions

This study constructed an evolutionary game model involving cold chain logistics enterprises, new energy vehicle manufacturers, and the government to analyze the realization of low-carbon operations in the cold chain logistics industry, and identified appropriate strategic choices for each stakeholder. The main findings of this study are as follows:

(1) Interplay of stakeholder decisions and evolutionary outcomes.

The decision-making behaviors of CCLEs, NEVMs, and the government are mutually influential, and their initial willingness to participate plays a critical role in shaping the evolutionary path. Higher initial participation levels of CCLEs and NEVMs in adopting low-carbon transformation and innovation lead to a faster convergence of the system toward the stable equilibrium $E_5(1, 1, 0)$, even in the absence of long-term government intervention. This highlights the importance of early engagement and strategic alignment among stakeholders for effective low-carbon transitions.

(2) Influence of carbon taxes and environmental externalities.

Carbon tax penalties (F_p, F_t) and environmental external costs (B_t) are identified as key determinants of stakeholder strategies. Stronger carbon tax penalties accelerate CCLEs' adoption of low-carbon strategies and reinforce NEVMs' incentives for innovation. Meanwhile, the magnitude of environmental external costs influences the government's regulatory intensity: lower levels of B_t induce stricter initial regulation, whereas higher levels of B_t result in weaker intervention. This demonstrates the necessity of aligning taxation and regulatory policies with the actual scale of externalities to ensure efficient governance.

(3) Combined effects of government subsidies and carbon penalties.

Government subsidies (M_p, M_t) and carbon penalties jointly influence the stability and effectiveness of the low-carbon transition in cold chain logistics. On one hand, moderate subsidies, corresponding to approximately 20%–40% of the low-carbon transformation cost, effectively enhance the willingness of CCLEs and NEVMs to adopt low-carbon strategies and foster collaborative behaviors across the supply chain. On the other hand, carbon penalties provide long-term incentives that promote continuous innovation and adherence to low-carbon practices. Excessive subsidies beyond this moderate range may reduce autonomous decision-making, potentially leading to suboptimal long-term outcomes. Overall, these results indicate that a balanced policy mix—combining appropriately scaled subsidies with carbon penalties—creates the most stable and effective incentive structure for coordinated emissions reduction across all stakeholders.

6.2. Management implications

The above findings offer valuable guidance for regulators and stakeholders in achieving the low-carbon goals of the cold chain industry. First, policymakers should strike a balance between carbon tax measures and subsidy policies to ensure both short-term effectiveness and long-term sustainability in driving low-carbon transformation. While higher carbon tax penalties can motivate firms to adopt low-carbon strategies and promote innovation, overreliance on such penalties might reduce the autonomy of market participants.

Second, enterprises should coordinate to build a low-carbon ecosystem, while downstream logistics firms adopt greener practices like route optimization and energy-efficient technologies. Subsidies at 20%–40% of transformation costs effectively promote collaboration, preserve autonomy, and support system stability, serving as a practical benchmark for policymakers.

Finally, effective collaboration between regulatory authorities and market participants is essential for achieving systemic improvements. Governments can create platforms for communication and cooperation, enabling stakeholders to align their objectives and work toward shared solutions. This collaborative approach not only enhances accountability but also strengthens the adaptability and stability of the low-carbon cold chain logistics system over time.

This study has several limitations that should be acknowledged. First, the model is developed under simplifying assumptions, which may not fully reflect the complexity of real-world market environments. Second, the analysis is largely theoretical and relies on simulated data, without empirical validation from actual cases. Future research should extend the framework by incorporating additional stakeholders, such as consumers, to capture more comprehensive dynamics of collaborative emission reduction.

Author contributions

Jiawen Zhang contributed to conceptualization, methodology, and writing the original draft. Changhong Zou contributed to software development and writing – review & editing. Hailong Li contributed to the formal analysis.

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Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors report there are no competing interests to declare.

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