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Research on Promotion and Application Strategy of Electric Equipment in Plateau Railway Tunnel Based on Evolutionary Game

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Abstract: Under China's modern development concept, it is necessary to promote the application of electric equipment to improve the construction environment of high-altitude railway tunnels and to address the efficiency reduction in high-altitude construction of traditional fuel oil equipment. Based on the analysis of the development status of electric equipment for tunneling projects in China, a tripartite evolutionary game approach is used to establish the game payment matrix of the government, equipment manufacturers, and construction units. The impact of the relevant parameters on the tripartite strategy is investigated based on numerical simulations. It has been shown that in the early stages of popularization and application, the government should actively regulate and control, and in the later stages of popularization and application, the government should play a leading role in market mechanisms. Evolutionary stability strategies are affected by the brand revenue that manufacturers earn through technological innovation on electric equipment and the additional research and development costs that need to be paid. The conclusions of this study can help provide a reference for the promotion and application strategy of electric equipment in China's plateau railway tunnels.

Keywords: evolutionary game; plateau railway tunnel; electric equipment; promotion and application; strategy

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1. Introduction

Compared to the plains, the plateau region has low temperature, low pressure, insufficient oxygen, and large temperature differences [1–3]. Conventional oil-powered machinery equipment suffers from severe power loss and increased usage costs [4]. In addition, because of the narrow construction site and limited ventilation, conventional oil-powered machinery and equipment emit additional pollutants and consume large amounts of oxygen, exacerbating the health hazards to workers in the tunnels from the anoxic environment on the plateau [5–8]. Additionally, the quality of Chinese workers has improved significantly along with the material standard of living of all Chinese people, and the demand of workers for a better working environment is increasing with each passing day [9,10]. The traditional hand-carried, shoulder-to-shoulder, dusty tunneling operation has struggled to be embraced by a fresh generation of workers. The destruction of sensitive and fragile areas of the ecological environment along the plateau railway by oil-powered mechanical equipment is also contrary to the building of ecological civilization, as required by China's 'carbon peak and carbon neutrality' goals [11–14]. In addition, rising domestic fuel prices have created multiple challenges for the use of conventional oil-powered machinery equipment [15]. In this paper, we aim to construct a three-agent evolutionary game model of the government, equipment manufacturers, and construction units, and study the promotion and application strategies of new energy equipment. At the same time, the influence of the relevant parameters on the tripartite strategy is analyzed through numerical simulation to provide suggestions and references for the application of new energy devices in railway tunneling projects on the plateau.

Several scholars have conducted studies from the perspective of tunneling equipment configuration in order to provide an application scheme for plateau railway tunneling equipment by integrating well-established equipment systems and optimizing selection strategies under the available technological means [16,17]. Taking the Guiyang-Guangzhou high-speed railway tunnel project as an example, Zhang et al. [18] analyzed several fundamental problems restricting the construction efficiency and safety. In developing and applying the rapid construction technology and matching equipment of the tunnel invert, the tunnel construction time was shortened. Song and Xia [19] proposed a self-organizing map-global particle swarm optimization algorithm and applied it to the optimization of the construction machinery unit combination for the F4 section of the Wushaoling Tunnel. After applying the optimization algorithm, the total carbon emissions were reduced by 88.4 percent compared to the original mechanical system configuration, which serves as a reference for other tunnel construction projects. Based on the analysis of environmental factors affecting the high-altitude construction of the Sichuan-Tibet railway tunnel, Xing and Feng [20] comprehensively considered the factors of equipment efficiency, economy, and construction quality, and provided advice on equipment selection for the key processes of drilling and blasting construction. Wang et al. [21] sorted out the policy conditions for the promotion and application of new energy equipment, combined with the unique environment of the plateau railway tunnel, summarized the advantages of electric equipment, and proposed applications. Under the modern development concept, it is necessary to implement electric equipment to achieve zero emissions during construction and to improve the construction environment of the plateau railway tunnel.

As an emerging industry, few scholars have attempted to analyze the promotion and application strategies of tunneling power equipment from a management perspective. Compared with electric equipment in tunnels, new energy vehicles have taken a long time to develop in the world [22–27], and their promotion and application strategies can be used as a reference.

In the promotion and application process of new energy vehicles, the government, manufacturers, consumers, and other interested subjects are commonly involved. Technical problems such as immature core technologies and imperfect safeguards for new energy vehicles are inevitable in the early stages of new energy vehicle development, limiting consumer enthusiasm for purchase [28–31]. Sun et al. [32] pointed out that increased R&D investment by vehicle enterprises can effectively motivate consumers to buy new energy vehicle products, stressing the importance of vehicle enterprises in promoting and applying new energy vehicles through the evolutionary game and system dynamics methods. However, excessive investment in R&D will increase the cost burden of enterprises. Therefore, in the early stage of technological development, government subsidies to enterprises are beneficial to stimulate their enthusiasm for innovation [33,34]. Li et al. [35] used a complex network evolutionary game method to explore the dynamic impacts of government policies on electric vehicle diffusion in different scale networks. The results show that production subsidies for enterprises are more favorable to the overall spread of electric vehicles than purchase subsidies for consumers. Yu et al. [36] pointed out through empirical analysis that the government's subsidy policy should be dynamically adjusted according to the specific situation of new energy vehicle enterprises. However, subsidization may lead to allocation unfairness and inefficiencies. A prior subsidy will constitute an effective incentive, and auto enterprises should also respond in a timely manner to the policies on the transformation and upgrading.

Some scholars [37,38] have discussed the influence of consumers' purchase behavior on enterprises' innovation behavior and emphasized the main role of the market in innovation. In this case, the government should consider appropriate purchase subsidies or tax incentives for consumers to stimulate market vitality and promote enterprise innovation [39]. Zhao et al. [40] further explored the impact of government subsidies for consumers on the proliferation of new energy vehicles. By building a three-stage evolutionary game model, Zhao noted that continuing to extend the period of financial subsidies for new energy vehicles at the national level is a powerful measure to support the sustainable development of the new energy vehicle industry in the context of COVID-19 pandemic.

Existing research has focused on the promotion of new energy vehicles in various ways. However, as an emerging industry, few scholars have attempted to analyze the promotion and application strategies of electric equipment for tunneling from a management perspective. Compared to new energy vehicles, consumers of tunnel electric equipment are mainly construction units. In China's railway construction system, construction units play the role of consumers more easily regulated by the government, and equipment manufacturers face a broader market, both of which value industry demonstration and leadership. On this basis, government regulation has a wider range of means and methods to apply. By adopting the three-party evolutionary game approach, numerous scholars [41–46] have investigated the strategies of three-party actors, supplemented by numerical simulation means, to explore the key impact factors in the game.

2. Background

The drilling and blasting method has a long history in the construction of railway tunnel. Because of its advantages of flexible and flexible adaptability, it is the most widely used method in the construction of railway tunnel. Compared to the TBM method, the drilling and blasting method is more refined and engineering disaster prevention techniques are more flexible when dealing with high-risk sections of the plateau and tunnel. It is a necessary means to deal with extreme risk sections of tunnels. However, the extreme working conditions on the plateau have led to traditional drilling and blasting construction, which is mainly artificial and cannot be carried out naturally. Therefore, it is necessary to improve the traditional drilling and blasting method in the plateau railway tunnel construction. Forming the supporting technology of the whole process mechanization can ensure the construction quality, reduce the labor intensity of operators, reduce the major safety risks of tunnel construction, and ensure the construction schedule.

Traditional drilling and blasting tunnel equipment can be classified into three categories according to their power source: (1) Pure diesel power equipment: common in muck transfer equipment, such as excavators, loaders, dumpers, etc. (2) Diesel-electric hybrid equipment: widely used in advance geological prediction, excavation operation, initial lining, the use of diesel power walking, electric power work. (3) Pure electric equipment: common in secondary lining equipment, such as invert trestle, waterproof board trolley, lining trolley, etc.

Currently, most of the mechanical equipment in tunnel construction is implemented with purely electric or diesel-electric hybrid power systems, but the muck-transfer lines are still dominated by purely diesel power equipment. Muck transfer operations accounted for approximately half of the total cycle time throughout the drilling and blasting method. The problem of mechanical devices and humans competing for oxygen in a plateau tunnel construction environment is prominent as the workload and transport distance increase. Required by the modern development strategy, Chinese well-known engineering machinery companies have introduced purely electric excavators, loaders, dumper machines, and other equipment to realize all-electric muck transfer equipment, which provides a viable solution to the efficiency reduction of traditional fuel oil equipment and the oxygen competition between equipment and humans in plateau tunnel construction.

The major advantages of the electric equipment include:

(1) Zero exhaust emissions, low noise, effectively improve the tunnel working environment. Compared with fuel-based equipment, electric equipment achieves zero tailpipe emissions [47]. In addition, the motor drive considerably reduces the noise in the working environment compared to the fuel equipment, and the improvement on the tunnel working environment is evident.

(2) It solves the problem of oxygen competition between fuel equipment and people, and relieves the pressure on the ventilation system. The oxygen content of the tunnel environment in the plateau is thin, so it is necessary to enhance ventilation and timely oxygen generation to replenish the oxygen content of the tunnel environment. In contrast to fuel equipment, electric equipment does not require oxygen-consuming combustion and does not consume oxygen in the tunnel, which solves the problem of oxygen competition between fuel equipment and people, and relieves the pressure of ventilation and oxygen production in the plateau tunnel [48,49].
(3) In the plateau environment, electric equipment ensures working efficiency. The efficiency of fuel oil equipment decreases as the oxygen content decreases due to altitude hypoxia [4]. Electric equipment effectively avoids this situation and ensures the operational efficiency of mechanical equipment.
(4) Electrical equipment has a long maintenance cycle and low maintenance costs, which reduce the cost of use. Engine systems of fuel equipment require regular replacement and maintenance of oil, oil filters, air filters, and fuel filters. As the altitude increases and the dust content and air humidity increase in the working environment, the frequency of maintenance of fuel equipment needs to increase and the cost of maintenance increases accordingly [50]. The maintenance of the frequency motor system of electric equipment is greatly reduced and the cost of maintenance is considerably reduced.
(5) The energy cost of electric equipment is much lower than that of oil equipment. Based on a crude calculation of fuel prices and electricity prices, the energy consumption cost of electric equipment is about half that of fuel equipment [51].

3. Methods

3.1. Problem Description and Basic Assumptions

In China, major infrastructure projects such as the Plateau Railway project and the Hong Kong-Zhuhai-Macao Bridge project are generally funded by the state. Such projects are a lifeline for the country's social and economic development and an essential platform for the country to encourage technological innovation [52–54]. In the construction of the railway tunnel project in the plateau, the promotion and application of electric equipment can considerably guarantee the ecological benefits of the plateau and lead to the transformation and upgrading of the traditional manufacturing industry into the field of environmental protection. In the future, how to promote and apply electric equipment to ensure the ecological benefits of the plateau in a large number of upcoming plateau railway projects, as represented by the Sichuan-Tibet Railway project [55], has become a focus of research and consideration for the government. At the present stage, however, the electric equipment for tunneling is still in the early stages of research and development. There are still application issues arising from immature technology, such as high equipment purchase costs, short battery life, and peak power upper limits, which limit the enthusiasm of construction units for generalization and application. Under the special conditions of the plateau railway tunnel, equipment manufacturers still have to pay a certain amount of financial and material resources to carry out technological innovations to provide a systematic and modular complete set of promotion and application programs [56]. In order to match electrical equipment with actual projects, front-line tunnel construction units need to carry out practical applications of electrical equipment, while assisting manufacturers in the trial and error of equipment technology innovations to enable technological updates and upgrades. As the technology of electric equipment is not yet mature, front-line tunnel construction units will inevitably increase the cost of maintenance and the purchase of spare equipment during their application.

In the promotion and application of electric equipment in the railway tunnel project on the plateau, the game process among government, equipment manufacturers, and construction units exist at different stages in the development of the electric equipment

(Figure 1). Based on the above analysis, the following assumptions are made in order not to change the essence of the analysis problem.

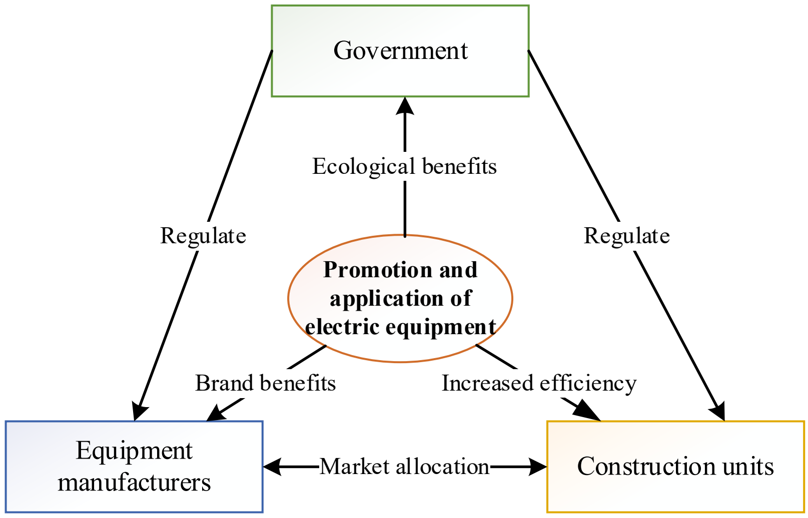


Figure 1. The relationship between the three agents.

Assumption 1. *Game agents.*

There are three main agents in the game, namely government, equipment manufacturers, and construction units, all of which have bounded rationality. They constantly adjust their strategic choices in the game and make decisions based on their own interests [57,58].

Assumption 2. *The behavior strategies of the government.*

The behavioral strategy sets of the government are S1 = {Positive regulation, Negative regulation}. Positive regulation means that the government takes certain measures to regulate the electrical equipment industry, including awarding incentives to manufacturers that implement technological innovations in electrical equipment, or subsidizing construction units that purchase and use electrical equipment. Negative regulation means that the government does not adopt any means to regulate the electrical equipment industry and does not intervene in whether manufacturers implement technological innovations in electrical equipment. At the same time, it does not interfere with the purchase and application of electrical equipment by frontline construction units and allows the market to adjust the configuration freely. The probabilities of Positive regulation and Negative regulation chosen by the government are x and $1 - x$ $(0 \leq x \leq 1)$, respectively.

Assumption 3. *The behavior strategies of the equipment manufacturers.*

The behavioral strategy sets of the equipment manufacturers are S2 = {Positive innovation, Negative innovation}. Positive innovation means that equipment manufacturers can iterate the configuration of electrical equipment through technological innovation, improve its construction efficiency and endurance time, and reduce the production cost of equipment by increasing the industrial chain, thus lowering the factory price. Negative regulation means that the manufacturer does not make technological innovations consistent with the maintenance of the current production technology of electric devices. The probabilities of Positive innovation and Negative innovation chosen by the equipment manufacturers are y and $1 - y$ $(0 \leq y \leq 1)$, respectively.

Assumption 4. *The behavior strategies of the construction units.*

The behavioral strategy sets of the construction units are S3 = {Positive application, Negative application}. Positive application refers to electric equipment purchased by the construction unit from the equipment manufacturer and applied in the tunnel construction line. Negative applications refer to the use of conventional equipment for production and construction, rather than electric equipment. The probabilities of Positive application and Negative application chosen by the construction units are z and $1 - z$ ($0 \leq z \leq 1$), respectively.

Assumption 5. *Hypotheses of relevant parameters in evolutionary game models and their meanings (Table 1 for details).*

Table 1. Hypotheses of relevant parameters in evolutionary game models and their meanings.

Agents	Parameters	Descriptions
Government	G_1	Government's initial benefits.
	G_2	The human, material, and financial costs incurred by the government in adopting Positive regulation strategies.
	G_3	The fines imposed by the government on construction units that pollute the environment during regulation and regulate.
	G_4	The government's industrial upgrading benefits that the equipment manufacturers carry out positive innovation of electric equipment.
	G_5	The government's ecological benefits that the construction units carry out positive application of electric equipment.
Equipment manufacturers	E_1	Equipment manufacturers' initial benefits.
	E_2	The equipment manufacturers' brand benefits from carrying out positive innovation of electric equipment to increase.
	E_3	The additional R&D costs incurred by the equipment manufacturers in adopting positive innovation for electric equipment.
	E_4	The additional incentives provided by the government to the equipment manufacturers that carry out positive innovation of electric equipment.
Construction units	C_1	Construction units' initial benefits.
	C_2	The additional costs incurred by maintenance and purchase of spare equipment due to immature technology when applying electric equipment for the construction units before the equipment manufacturer carries out positive innovation.
	C_3	The reduced costs that the construction unit applies the electric equipment after the equipment manufacturer carries out positive innovation.
	C_4	The government subsidies for the construction units by carrying out positive application of electric equipment.

3.2. Evolutionary Game Model

Based on the behavioral strategies of the government, equipment manufacturers, and construction units, it can be concluded that there are eight game combinations among them, as shown in Table 2. See Table 3 for the perceived payoff matrix for the three-agents game.

Table 2. Set of three-agent game strategies.

<table>
<tr><th colspan="2" rowspan="4"></th><th colspan="4">Equipment Manufacturers</th></tr>
<tr><th colspan="2">Positive Innovation (y)</th><th colspan="2">Negative Innovation ($1-y$)</th></tr>
<tr><th colspan="4">Construction Units</th></tr>
<tr><th>Positive Application (z)</th><th>Negative Application ($1-z$)</th><th>Positive Application (z)</th><th>Negative Application ($1-z$)</th></tr>
<tr><td rowspan="2">Government</td><td>Positive regulation (x)</td><td>(Positive regulation, Positive innovation, Positive application)</td><td>(Positive regulation, Positive innovation, Negative application)</td><td>(Positive regulation, Negative innovation, Positive application)</td><td>(Positive regulation, Negative innovation, Negative application)</td></tr>
<tr><td>Negative regulation ($1-x$)</td><td>(Negative regulation, Positive innovation, Positive application)</td><td>(Negative regulation, Positive innovation, Negative application)</td><td>(Negative regulation, Negative innovation, Positive application)</td><td>(Negative regulation, Negative innovation, Negative application)</td></tr>
</table>

Table 3. Perceived payoff matrix for the three-agents game.

Behavioral Strategies	Government's Benefits	Equipment Manufacturers' Benefits	Construction Units' Benefits
(Positive regulation, Positive innovation, Positive application)	$G_1 - G_2 + G_4 + G_5 - E_4 - C_4$	$E_1 + E_2 - E_3 + E_4$	$C_1 + C_3 + C_4$
(Positive regulation, Positive innovation, Negative application)	$G_1 - G_2 + G_3 + G_4 - E_4$	$E_1 + E_2 - E_3 + E_4$	$C_1 - G_3$
(Positive regulation, Negative innovation, Positive application)	$G_1 - G_2 + G_5 - C_4$	E_1	$C_1 - C_2 + C_4$
(Positive regulation, Negative innovation, Negative application)	$G_1 - G_2 + G_3$	E_1	$C_1 - G_3$
(Negative regulation, Positive innovation, Positive application)	$G_1 + G_4 + G_5$	$E_1 + E_2 - E_3$	$C_1 + C_3$
(Negative regulation, Positive innovation, Negative application)	$G_1 + G_4$	$E_1 + E_2 - E_3$	C_1
(Negative regulation, Negative innovation, Positive application)	$G_1 + G_5$	E_1	$C_1 - C_2$
(Negative regulation, Negative innovation, Negative application)	G_1	E_1	C_1

3.3. Replicator Dynamic Analysis

Based on the above analysis and evolutionary principles of evolutionary game theory, when the expected payoff of a strategy is higher than the overall average expected payoff, the strategy will evolve and evolve in the system. The evolution process can be described by the replicator kinetic equation.

3.3.1. Government

Assume that the payoff expectation is U_{11} when government chooses Positive regulation, the payoff expectation is U_{12} when government chooses Negative regulation, and average payoff expectation is U_1.

$$\begin{aligned} U_{11} &= yz(G_1 - G_2 + G_4 + G_5 - E_4 - C_4) + y(1-z)(G_1 - G_2 + G_3 + G_4 - E_4) \\ &+ z(1-y)(G_1 - G_2 + G_5 - C_4) + (1-y)(1-z)(G_1 - G_2 + G_3) \end{aligned} \tag{1}$$

$$U_{12} = yz(G_1 + G_4 + G_5) + y(1-z)(G_1 + G_4) + z(1-y)(G_1 + G_5) + (1-y)(1-z)G_1 \tag{2}$$

$$U_1 = xU_{11} + (1-x)U_{12} \tag{3}$$

According to the stability theorem of differential equation and government's replication dynamic equation, it can be known the government's replication dynamic equation is as follows.

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(U_{11} - U_1) = x(1-x)(U_{11} - U_{12}) \\ &= -x(1-x)[G_2 - G_3 + yE_4 + z(C_4 + G_3)] \end{aligned} \tag{4}$$

The derivative of the replicator dynamics equation of x can be further calculated below

$$\frac{dF(x)}{dx} = -(1-2x)[G_2 - G_3 + yF_4 + z(G_3 + C_4)] \tag{5}$$

Then, three circumstances are discussed separately according to Formula (5).

Obviously, $x = 0$, $x = 1$, $z = \frac{G_3 - G_2 - yF_4}{G_3 + G_4}$ are the roots of $F(x) = 0$. Based on the stability theorem put forward by Friedman in 1991, when $F(x) = 0$, $F'(x) \le 0$, x is an ESS.

(1) When $z = \frac{G_3 - G_2 - yF_4}{G_3 + G_4}$, then for any $x \in [0, 1]$, $F(x) = 0$, $\frac{dF(x)}{dx} = 0$, the x-axis is in a stable state, and any strategies of the government are stable.
(2) When $0 \le z < \frac{G_3 - G_2 - yF_4}{G_3 + G_4}$, $\frac{dF(x)}{dx}|_{x=0} > 0$, $\frac{dF(x)}{dx}|_{x=1} < 0$, we can see that $x = 1$ is the only ESS. At this time, the government chooses Positive regulation is the optimal strategy.
(3) When $1 \ge z > \frac{G_3 - G_2 - yF_4}{G_3 + G_4}$, $\frac{dF(x)}{dx}|_{x=0} < 0$, $\frac{dF(x)}{dx}|_{x=1} > 0$, we can see that $x = 0$ is the only ESS. At this time, the government chooses Negative regulation is the optimal strategy.

The dynamic evolution diagram of government's decision making is shown in Figure 2.

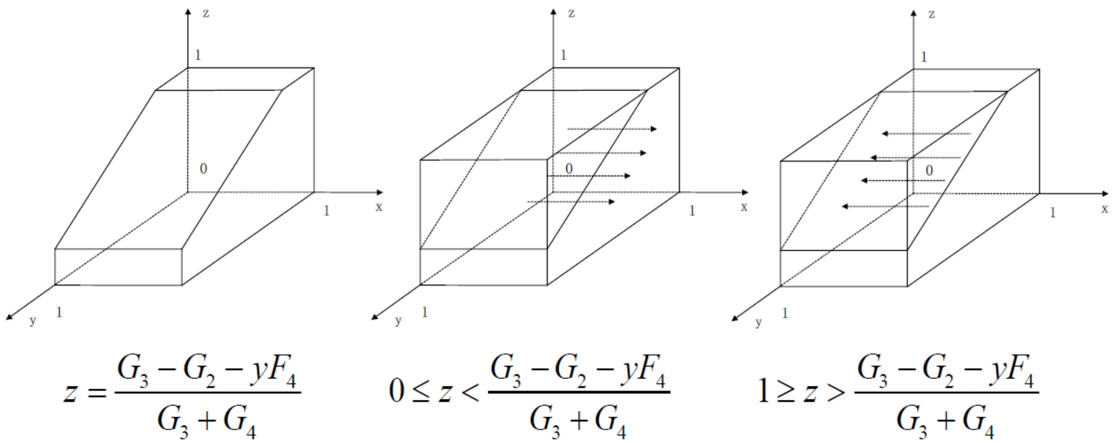


Figure 2. Dynamic evolution diagram of government's decision-making.

3.3.2. Equipment Manufacturers

Assume that the payoff expectation is U_{21} when equipment manufacturers choose Positive innovation, the payoff expectation is U_{22} when equipment manufacturers choose Negative innovation, and average payoff expectation is U_2.

$$\begin{aligned} U_{21} &= xz(F_1 + F_2 - F_3 + F_4) + x(1-z)(F_1 + F_2 - F_3 + F_4) \\ &+ z(1-x)(F_1 + F_2 - F_3) + (1-x)(1-z)(F_1 + F_2 - F_3) \end{aligned} \tag{6}$$

$$U_{22} = [xz + x(1-z) + z(1-x) + (1-x)(1-z)]F_1 \tag{7}$$

$$U_2 = yU_{21} + (1-y)U_{22} \tag{8}$$

According to stability theorem of differential equation and equipment manufacturers' replication dynamic equation, it can be known the equipment manufacturers' replication dynamic equation is as follows.

$$F(y) = \frac{dy}{dt} = y(U_{21} - U_2) = y(1-y)(U_{21} - U_{22}) = y(1-y)(F_2 - F_3 + xF_4) \tag{9}$$

The derivative of the replicator dynamics equation of y can be further calculated below

$$\frac{dF(y)}{dy} = (1-2y)(F_2 - F_3 + xF_4) \tag{10}$$

Then, three circumstances are discussed separately according to Formula (10).

Obviously, $y = 0$, $y = 1$, $x = \frac{F_3 - F_2}{F_4}$ are the roots of $F(y) = 0$. Based on the stability theorem put forward by Friedman in 1991, when $F(y) = 0$, $F'(y) \leq 0$, y is an ESS.

(1) When $x = \frac{F_3 - F_2}{F_4}$, then for any $y \in [0, 1]$, $F(y) = 0$, $\frac{dF(y)}{dy} = 0$, the y-axis is in a stable state, and any strategies of the equipment manufacturers are stable.

(2) When $0 \leq x < \frac{F_3 - F_2}{F_4}$, $\frac{dF(y)}{dy}|_{y=0} < 0$, $\frac{dF(y)}{dy}|_{y=1} > 0$, we can see that $y = 0$ is the only ESS. At this time, the equipment manufacturers choose negative innovation is the optimal strategy.

(3) When $1 \geq x > \frac{F_3 - F_2}{F_4}$, $\frac{dF(y)}{dy}|_{y=0} > 0$, $\frac{dF(y)}{dy}|_{y=1} < 0$, we can see that $y = 1$ is the only ESS. At this time, the equipment manufacturers choose positive innovation is the optimal strategy.

The dynamic evolution diagram of equipment manufacturers' decision making is shown in Figure 3.

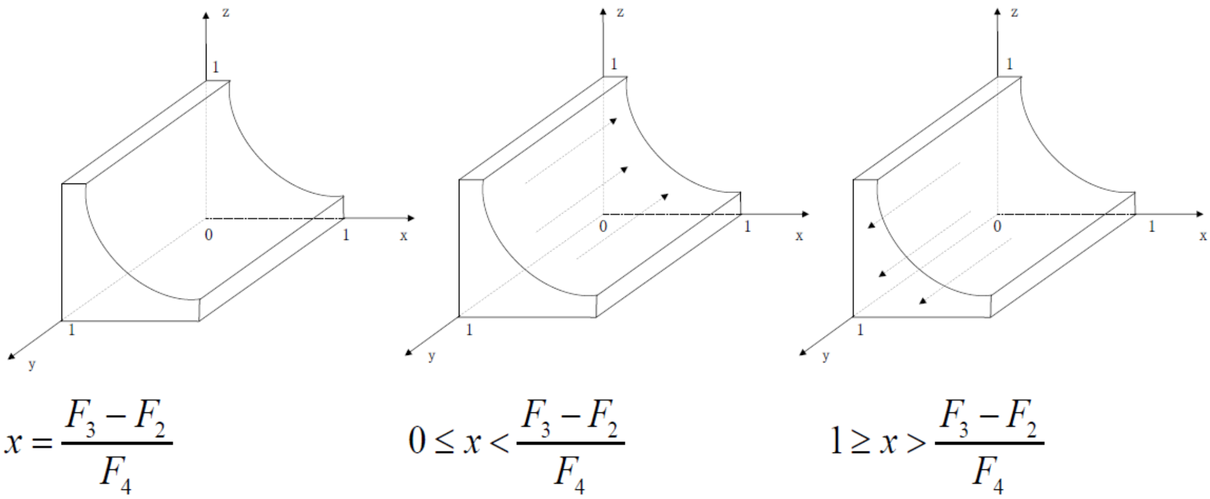


Figure 3. Dynamic evolution diagram of equipment manufacturers' decision-making.

3.3.3. Construction Units

Assume that the payoff expectation is U_{31} when construction units choose Positive application, the payoff expectation is U_{32} when construction units choose Negative innovation, and average payoff expectation is U_3

$$\begin{aligned} U_{31} = xy(C_1 + C_3 + C_4) + x(1-y)(C_1 - C_2 + C_4) + \\ y(1-x)(C_1 + C_3) + (1-x)(1-y)(C_1 - C_2) \end{aligned} \quad (11)$$

$$U_{32} = xy(C_1 - G_3) + x(1-y)(C_1 - G_3) + [y(1-x) + (1-x)(1-y)]C_1 \quad (12)$$

$$U_3 = zU_{31} + (1-z)U_{32} \quad (13)$$

According to stability theorem of differential equation and construction units' replication dynamic equation, it can be known the construction units' replication dynamic equation is as follows.

$$\begin{aligned} F(z) = \frac{dz}{dt} = z(U_{31} - U_3) = z(1-z)(U_{31} - U_{32}) \\ = z(1-z)[xC_4 - (1-y)C_2 + yC_3 + xG_3] \end{aligned} \quad (14)$$

The derivative of the replicator dynamics equation of z can be further calculated below

$$\frac{dF(z)}{dz} = (1-2z)(xC_4 - (1-y)C_2 + yC_3 + xG_3) \quad (15)$$

Then, three circumstances are discussed separately according to Formula (15).

Obviously, $z = 0$, $z = 1$, $y = \frac{C_2 - x(C_4+G_3)}{C_2+C_3}$ are the roots of $F(z) = 0$. Based on the stability theorem put forward by Friedman in 1991, when $F(z) = 0$, $F'(z) \le 0$, z is an ESS.

(1) When $y = \frac{C_2 - x(C_4+G_3)}{C_2+C_3}$, then for any $z \in [0, 1]$, $F(z) = 0$, $\frac{dF(z)}{dz} = 0$, the z-axis is in a stable state, and any strategies of the equipment manufacturers are stable.

(2) When $0 \le y < \frac{C_2 - x(C_4+G_3)}{C_2+C_3}$, $\frac{dF(z)}{dz}|_{z=0} < 0$, $\frac{dF(z)}{dz}|_{z=1} > 0$ we can see that $z = 0$ is the only ESS. At this time, the construction units choose negative application is the optimal strategy.

(3) When $1 \ge y > \frac{C_2 - x(C_4+G_3)}{C_2+C_3}$, $\frac{dF(z)}{dz}|_{z=0} > 0$, $\frac{dF(z)}{dz}|_{z=1} < 0$ we can see that $z = 1$ is the only ESS. At this time, the construction units choose positive application is the optimal strategy.

The dynamic evolution diagram of construction units' decision making is shown in Figure 4.

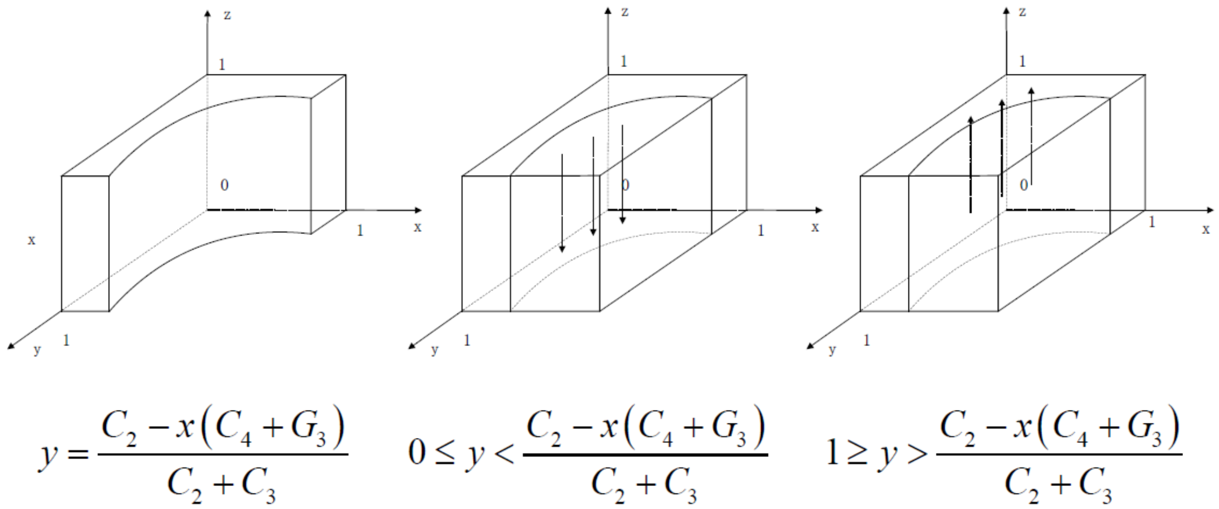


Figure 4. Dynamic evolution diagram of construction units' decision-making.

3.4. Tripartite Game Equilibrium Solution

According to the Jacobian matrix theory which was proposed by Friedman, there are eight local equilibrium points in the system: $P_1(0,0,0)$, $P_2(0,0,1)$, $P_3(0,1,0)$, $P_4(0,1,1)$, $P_5(1,0,0)$, $P_6(1,0,1)$, $P_7(1,1,0)$, and $P_8(1,1,1)$. The stability of the equilibrium point is obtained by analyzing the local stability of the Jacobian matrix. The Jacobian matrix of this system is composed of differential Equations (5), (10) and (15) as shown in the Formula (16).

$$J = \begin{bmatrix} -(1-2x)[G_2 - G_3 + yF_4 + z(G_3+C_4)] & -x(1-x)F_4 & -x(1-x)(G_3+C_4) \\ y(1-y)F_4 & (1-2y)(F_2 - F_3 + xF_4) & 0 \\ z(1-z)(C_4+G_3) & z(1-z)(C_2+C_3) & (1-2z)(xC_4 - (1-y)C_2 + yC_3 + xG_3) \end{bmatrix} \quad (16)$$

The eigenvalues of Jacobian matrix are obtained by substituting eight equilibrium points into Jacobian matrix, as shown in Table 4.

Table 4. Eigenvalues of Jacobian matrix.

Equilibrium Point	λ_1	λ_2	λ_3	Stability Condition
P_1 (0,0,0)	$E_2 - E_3$	$G_3 - G_2$	$-C_2$	$E_2 - E_3 < 0$, $G_3 - G_2 < 0$
P_2 (0,0,1)	C_2	$E_2 - E_3$	$-G_2 - C_4$	unstable point
P_3 (0,1,0)	C_3	$E_3 - E_2$	$G_3 - G_2 - E_4$	unstable point
P_4 (0,1,1)	$E_3 - E_2$	$-C_3$	$-C_4 - E_4 - G_2$	$E_3 - E_2 < 0$
P_5 (1,0,0)	$G_2 - G_3$	$C_4 - C_2 + G_3$	$E_2 - E_3 + E_4$	unstable point
P_6 (1,0,1)	$C_4 + G_2$	$E_2 - E_3 + E_4$	$C_2 - C_4 - G_3$	unstable point
P_7 (1,1,0)	$C_3 + C_4 + G_3$	$E_4 + G_2 - G_3$	$E_3 - E_2 - E_4$	unstable point
P_8 (1,1,1)	$G_2 + C_4 + E_4$	$-C_3 - C_4 - G_3$	$E_3 - E_2 - E_4$	unstable point

The possible stable equilibrium points in the game are P_1 (0,0,0), P_4 (0,1,1). However, the satisfaction of the stability condition at the equilibrium point still requires further analysis.

If $E_2 - E_3 < 0$, $G_3 - G_2 < 0$, that means the equipment manufacturers' brand benefits that carrying out positive innovation of electric equipment to increase is less than the additional R&D costs incurred by the equipment manufacturers in adopting positive innovation for electric equipment. In addition, the fines imposed by the government on construction units that pollute the environment during supervision and regulation are less than the human, material, and financial costs incurred by the government when it adopts a positive regulation strategy. In this case, Negative regulation, Negative innovation, Negative application is ESS.

If $E_3 - E_2 < 0$, that means the equipment manufacturers' brand benefits that carrying out positive innovation of electric equipment to increase is greater than the additional R&D costs incurred by the equipment manufacturers in adopting positive innovation for electric equipment. Negative regulation, Positive innovation, Positive application is ESS.

4. Numerical Example

4.1. Case Description and Parameter Settings

By analyzing the game of the government, the equipment manufacturers, and the construction units, it can be found that the equilibrium points of the evolution of the three parties are P_1 (0,0,0) and P_4 (0,1,1) under certain parameters. Since point P_1 (0,0,0) has no research significance, the following research is mainly conducted for P_4 (0,1,1). The parameter condition of point P_4 is limited to $E_3 - E_2 < 0$. This equilibrium point is consistent with the tendency of government regulation to go to 0 under long-term development conditions, and the production and application of new energy devices is freely regulated by the market, in accordance with the law of market evolution. Based on the equations of the tripartite replicator dynamics and the analysis of the equilibrium stable point, the strategies of the tripartite cooperative behavior are directly affected by the initial intentions of the tripartite and the variable parameters. The initial parameter settings are listed in Table 5. Meanwhile, the tripartite initial intentions are set to (0.2,0.2,0.2).

Table 5. The initial parameter settings.

Agents	Government					Equipment Manufacturers				Construction Units			
Parameter	G_1	G_2	G_3	G_4	G_5	E_1	E_2	E_3	E_4	C_1	C_2	C_3	C_4
Assignment	100	5	5	10	10	100	15	10	5	100	10	15	5

Numerical simulations were performed using MATLAB R2021a software and the results are shown in Figure 5. It can be seen from Figure 5 that the evolutionary stable state of the system is (0,1,1), which is consistent with the above conclusion, and the model is effective.

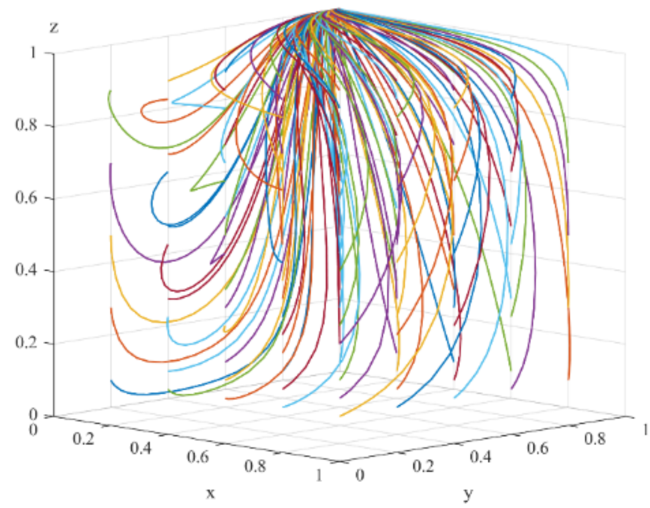


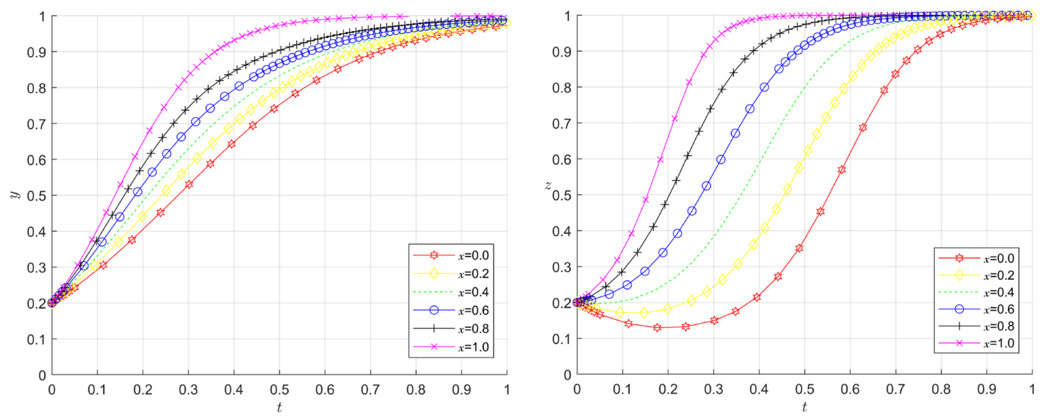
Figure 5. Evolution path of three-agent game.

4.2. The Impact of Selecting an Initial Change of Strategy on Evolutionary Results

4.2.1. Government

When the initial intention of equipment manufacturers and construction units remain unchanged ($y = z = 0.2$), selected the initial strategy x of the government is (0.0, 0.2, 0.4, 0.6, 0.8, 1.0), the influence of tripartite initial intention on their behavioral strategies is analyzed.

Figure 6a shows that the equipment manufacturers' intention y converges to 1 regardless of the government's initial intention. As the initial intention of the government department increases, the convergence rate of the equipment manufacturer's intention accelerates. Therefore, equipment manufacturers will innovate electric equipment positively regardless of the government's strategy, and their innovation intentions will increase as the government's regulate strategy intentions increase.



(**a**) (**b**)

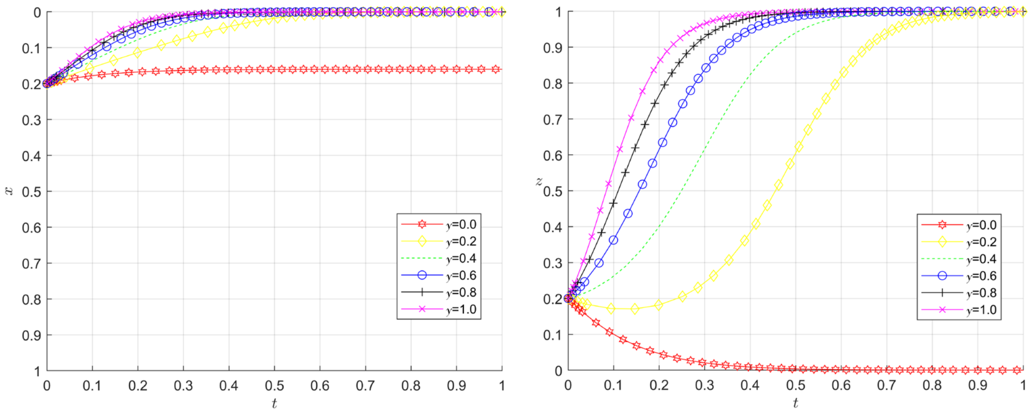
Figure 6. Evolution path of initial intention x change. (**a**) The effect on the y value, (**b**) The effect on the z value.

Figure 6b shows that the construction units' intention y converges to 1 regardless of the government's initial intention. As the initial intention of the government department increases, the convergence rate of the construction units' intention accelerates. Therefore, construction units will apply electric equipment positively regardless of the government's strategy, and their application intentions will increase as the government's regulate strategy intentions increase.

4.2.2. Equipment Manufacturers

When the initial intention of government and construction units remain unchanged ($x = z = 0.2$), the selected initial strategy y of the government is (0.0, 0.2, 0.4, 0.6, 0.8, 1.0), the influence of tripartite initial intention on their behavioral strategies is analyzed.

Figure 7a shows that the government's intent x converges to zero when the equipment manufacturers' initial intent is non-zero. At the same time, with the increase of the initial intention of the equipment manufacturers, the convergence speed of the intention x of the government accelerates, which means that when the equipment manufacturers have the positive intention to innovate, the government departments gradually tend to regulate negatively, while when the equipment manufacturers have no intention to innovate, the government departments have the intention to regulate positively.



(**a**) (**b**)

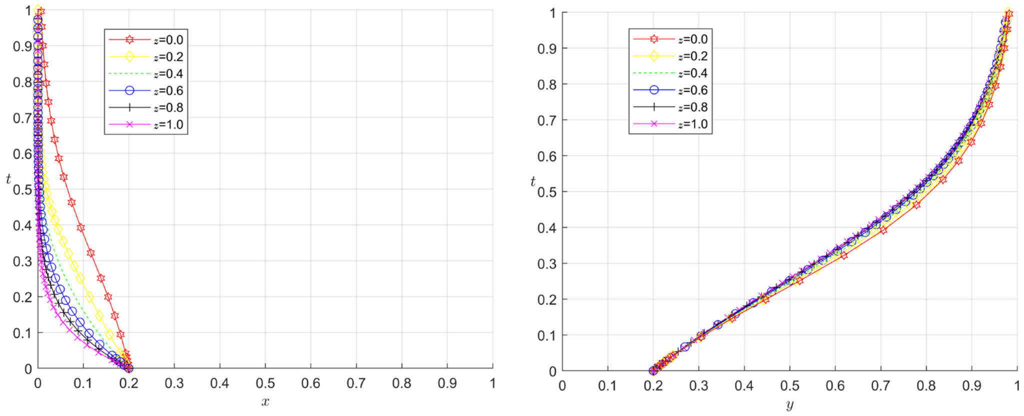
Figure 7. Evolution path of initial intention y change. (**a**) The effect on the x value, (**b**) The effect on the z value.

Figure 7b shows that shows that the construction units' intent z converges to 1 when the equipment manufacturers' initial intent is non-zero. At the same time, with the increase of the initial intention of the equipment manufacturers, the convergence rate of the construction units' intention z is accelerated, indicating that when the equipment manufacturers have the positive intention to innovate, the construction units' intention to apply electric equipment increases, and when the equipment manufacturers have no intention to innovate, the construction units gradually have negative intention to apply.

4.2.3. Construction Units

When the initial intention of government and equipment manufacturers remain unchanged ($x = y = 0.2$), the selected initial strategy z of the construction units is (0.0, 0.2, 0.4, 0.6, 0.8, 1.0), the influence of tripartite initial intention on their behavioral strategies is analyzed.

Figure 8a shows that the government's intention x converges to 0 regardless of the initial intention of the construction units. At the same time, with the increase of the initial intention of the construction unit, the convergence speed of the government's intention x is accelerated, indicating that no matter what the strategy of the construction unit is, the government will gradually give up the regulation of electric equipment, and its regulation intention will decrease with the increase of the application intention of the construction unit.



(**a**) (**b**)

Figure 8. Evolution path of initial intention z change. (**a**) The effect on the x value, (**b**) The effect on the y value.

Figure 8b shows that the equipment manufacturer's intention y converges to 1 regardless of the initial intention of the construction units, and the equipment manufacturer's innovation intention is not greatly affected by the application strategy of the construction units.

4.3. The Impact of Selecting a Parameter Change of Strategy on Evolutionary Results

According to the replica dynamics equation and the equilibrium stationary point analysis, the three-agent behavior strategy can be affected by some parameters. On the basis of unchanged initial parameters (Table 5), sensitivity analysis was carried out by changing parameters such as G_3, E_4, C_4 and E_3.

The following conclusions are drawn from the numerical simulations.

1. When the government departments regulate the implementation of environmental pollution of construction units to impose fines, construction units tend to positively apply (see Figure 9).
2. When the incentives of government departments for manufacturers to carry out electric equipment technology innovation increase, equipment manufacturers tend to positively innovate (see Figure 10).
3. When the construction units get more subsidies from government departments through the deployment and application of electric equipment, the construction unit tends to positively apply it (see Figure 11).

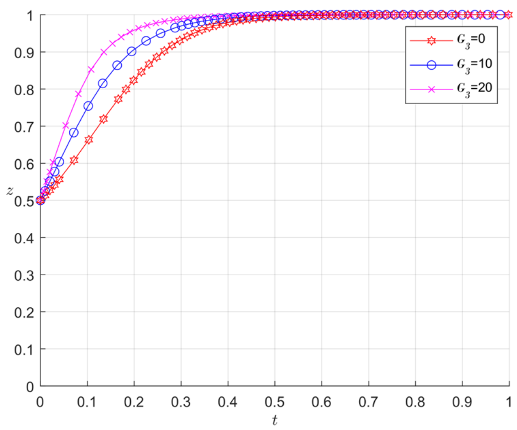


Figure 9. The impact of G_3 on evolutionary results of construction units.

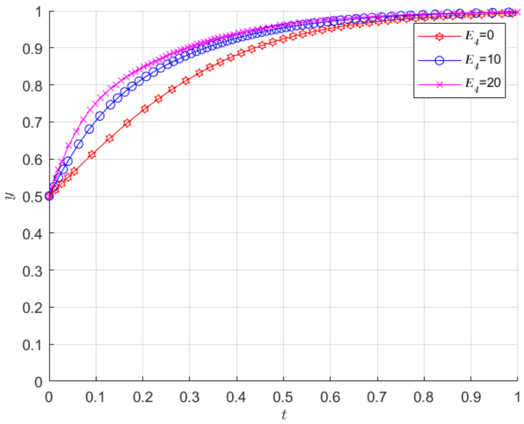


Figure 10. The impact of E_4 on evolutionary results of equipment manufacturers.

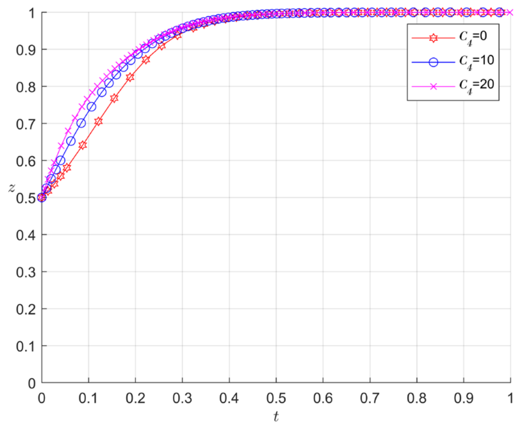


Figure 11. The impact of C_4 on evolutionary results of equipment manufacturers.

In addition, it can be seen from Figure 12 that when E_3 is greater than E_2 the equipment manufacturers tend to innovate electric equipment negatively. In contrast, when E_2 is greater than E_3 the equipment manufacturers tend to innovate electric equipment positively.

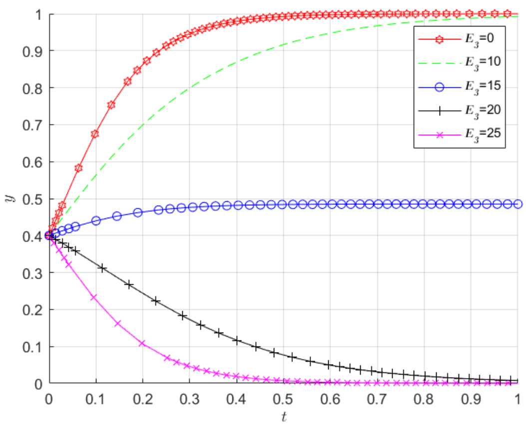


Figure 12. The impact of E_3 on evolutionary results of equipment manufacturers.

5. Results and Discussion

In this paper, we develop a three-agent evolutionary game model among the government, equipment manufacturers, and construction units based on the state of development of the electrical equipment industry in a plateau railway tunnel and analyze the game relations and factors that influence the strategic choices of the parties. Based on the above equilibrium points and the results of numerical simulation, the following conclusions and recommendations are drawn.

(1) In the early stage of the development of the new energy industry, the government should actively carry out regulation and encourage equipment manufacturers to innovate and upgrade the electric equipment. Based on the strengthened certification of electric equipment specifications, preferential policies such as accelerated depreciation, value-added tax, and income tax reduction should be given to electric equipment manufacturers to reduce risks for equipment manufacturers in the early stages of research and development. At the same time, the government should adopt mandatory and encouraging policies for construction units: improve market acceptance and application demonstration of electric equipment through the promulgation of preferential policies such as tax reduction and exemption. By imposing a plateau pollution tax, the cost of plateau applications of conventional fuel oil equipment is increased, resulting in a relative reduction in expenditure on electric equipment. The government may take incentives such as bid requirements and contract performance to require and encourage the participating construction units to purchase a certain proportion of electric equipment in the first line, thereby promoting the promotion and application of electric equipment. In the long-term context, to achieve the goal of promoting and applying electric equipment in railway tunnels on the plateau, government departments must be market-oriented, play a leading role in market mechanisms, and encourage innovative production to drive the industry.
(2) The innovation enthusiasm of equipment manufacturers is affected by their innovation cost. In the early stage of industrial development, the high cost of innovation will affect the innovation decisions of equipment manufacturers, and the government should give a certain level of support. Equipment manufacturers should actively respond to calls from government departments to formulate a strategy for electric equipment development, strengthen research and development of core technologies for electric equipment, and actively carry out technological updates and iterations to enhance market competitiveness. At the same time, the equipment manufacturer should take the initiative to contact line construction units, understanding plateau tunnel construction specifically needs a line of electric equipment, actively carry out live trial, plateau tunnel around the overall cost and battery life, the size of the equipment, plateau, such as the stability and safety charging pile in actual combat vehicle technology research and development and the core components technical research.
(3) Construction units should actively respond to the call of government departments, take the initiative to deploy electric equipment in the tunnel construction line, take the lead in demonstration and application, improve the working environment of plateau tunnels, and gradually ban traditional fuel oil equipment with the trend of industrial upgrading. At the same time, the construction unit shall be equipped with auxiliary plant trial and error, technological innovation for plateau railway tunnel space is relatively closed, low pressure, low oxygen, dust, damp environment, and the possibility of high geothermal, water inrush and gas outburst, rock burst mud such as geological environment, actively summarize feedback early application of electric equipment, application problem, and the key technical problems in the pilot demonstration area, accelerating industrial upgrading.

The electric equipment provides a feasible solution to the problem of reducing the efficiency of traditional fuel equipment and the oxygen competition between equipment and people in the construction of plateau railway tunnel, which greatly ensures the health of frontline construction personnel and the fragile ecological environment of plateau, and the value it brings is immeasurable.

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