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Tripartite Evolution Game of Railway Safety Supervision Under the Influence of Collusion Within the Enterprise

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ABSTRACT The National Railway Administration of the People's Republic of China, the China State Railway Group Co., Ltd. and the front-line staff are the three main stakeholders in the railway safety supervision system, and their decision-making behaviors will directly affect the railway safety. In this paper, based on the organizational hierarchy of railway safety supervision system in China and accidental cause mechanism, considering the influence of collusion rewards and punishments between enterprise and staff, the tripartite evolutionary game model is built. According to the actual data of 2018, the complex phenomena and evolution forms in the game process are simulated, and the behavior evolution rules of the three parties in the game are revealed, as well as the controllable factors and methods for the evolution direction of the system are explored. Evolutionary simulation shows that the railway safety supervision system is at an ideal state, and the current policy and management system are in a scientific scope. Some parameters should be reasonably controlled, so as to guide the system evolution in the direction of Pareto optimality. The research can provide a theoretical reference for coordinating the relationship among the three parties, formulating regulatory policies and improving the ability to manage and control risks for railroads.

INDEX TERMS Railway safety, supervision, system dynamics, tripartite game, evolutionary game.

I. INTRODUCTION

Railway mainlines run through China all directions. China's railway is changing China with unprecedented depth and breadth. By the end of July 2020, China's operating railway had reached 141,400 kilometers which had the world's second-longest mileage. The high-speed railway had come towards 36,000 kilometers, ranking the first place over the world. In the first seven months of 2020, the total delivery volume of railway freight was 2.01 billion tons, with its growing by 4.3% year on year. Especially in July, the China's national railway delivered 320 million tons of cargoes, an increase of 8.5% annually, reflecting the solid transportation safety assurance behind the steady and positive development of the Chinese economy. In August 2020, China Railway (short for China State Railway Group Co., Ltd.) issued the 'Outline of Powerful Nation Railway Advance Planning in the new era', which benchmarks to an advanced international standard and depicts a blueprint in the new era. However, there are still security vulnerabilities in the environment along the railway, quality of train operation equipment, construction on revenue lines and site operations, and the security risk is outstanding. According to official data from the National Railway Administration, between 2011 and 2019, there were a tremendous devastating railway traffic accident, a major accident and 21 serious accidents. During the nine years, a total of 10,109 people died in railway accidents. These accidents exposed the flaws and loopholes in safety supervision. The study of evolutionary game is beneficial to excavate the decision logic behind the behaviors of stakeholders, furthermore reduce or even avoid accidents at the root.

Rasmussen [1], the founder of system safety, believes that the accident is caused by the combined effect of efficiency gradient and benefit gradient in a highly competitive environment, which leads to the systematic migration of the subject behavior to the boundary of the accident. Risk management

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is a controllable process, and evolutionary game theory can provide ideas for analyzing the logic behind the behavior and strategy of system subjects in risk management and control. At present, scholars have introduced the evolutionary game theory into many safety supervision fields, such as project bidding [2], water conservancy engineering [3], coal mining enterprises [4], online car-hailing [5], and airlines [6]. Surrounding the supervision mechanisms, such as market constraints, industry self-discipline, government administrative supervision, stakeholder supervision, the oversight of the news media and the general public, and from the perspective of economics or management, the strategic choices of participants are analyzed. Game participation has gradually expanded from two-agent to three or even more, which enriches the game scene and makes the research more realistic. Song *et al.* [7] carried out an evolutionary game study between food enterprises and government regulators, and drew a conclusion that government supervision alone could not effectively solve the problem of false information in the food safety supervision system. Yang *et al.* [8] analyzed the behavior evolution process of regulators, energy enterprises and whistleblowers in China's energy regulatory system, and proposed that proper measures should be taken in the process of energy regulatory authorities for improving the proportion of true whistleblowing on energy issues by the public. Zhang *et al.* [9] built a general aviation safety supervision evolutionary game model based on the tripartite interaction among safety regulators, general aviation enterprises and employees. And then analyzed the evolutionary path and characteristics of each participant in supervision. Guo *et al.* [10] analyzed the optimization strategy of reward and punishment mechanism based on the system dynamics model of the tripartite game of the project owner (PO), construction supervising engineer (CSE) and the construction contractor (CC). Zhang *et al.* [11] constructed the multi-parties evolutionary game model between the government department and the shipping enterprise, the shipping enterprise and the crew. In addition, the influence of supervision cost, supervision intensity, punishment strength, casualty compensation standard and operating cost on the game were analyzed. Li *et al.* [12] constructed an evolutionary game model composed of high-speed railway companies and multiple clients, and analyzed the dynamic selection of each participant's strategy. You *et al.* [13] discusses the interaction game among coal mine owners, coal mine safety supervision departments and ordinary miners in the internal safety inspection system of coal enterprises in China, and analyzes the stability of stakeholder interaction under different scenarios and the influence of different reward and punishment strategies on the game process and equilibrium state. In view of the entrusted transportation management mode of China's high-speed railway, Li *et al.* [14] established an evolutionary game model and carried out the system dynamics simulation, in which the game players are composed of three parties: the high-speed railway company, the National Railway Administration and the entrusted railway administration. Feng *et al.* [15] introduced two regulatory agencies and one regulatory agency into the railway transportation safety supervision system, established a railway transportation safety supervision model based on the multi-system evolutionary game and system dynamics, and simulated the decision-making process of players under different conditions.

The existing researches have been conducted from the perspective of economics or management on the construction of the evolutionary game model, and focused on the analysis of influencing factors and the dynamic selection of strategies for the bounded rational multi-stakeholder group under the comprehensive safety supervision system combining multiple supervision mechanisms. However, there are still two defects. One, the role of vulnerability accident causing mechanism in system safety theory in safety supervision system is not considered; the other, the interference of collusion behavior in the enterprise internal control system to the evolutionary process is not considered. Railway safety supervision is a complex, arduous and long task. The safety supervision agency of the National Railway Administration and the enterprise management level of China Railway has important regulatory responsibilities. Railway front-line staff have strict professional qualification access and bear liability to accident directly, E.g.: lineman, bridge and tunnel patrolling man, bridge builder, signalman, communications worker, catenary worker, locomotive fitter, rolling stock electricians and so on. As an independent laborer, the staff has his own utility function and will make a choice and adjustment that can bring him the maximum utility after analyzing the strategic choices and behaviors of other players.

It is worth noting that China Railway carries out internal supervision on front-line staff, and the supervision principle of ''consistency'' between staff and management objectively provides the hotbed of collusion between enterprises and employees. Thus, in this paper, starting from the system safety theory, based on the current organization hierarchy of railway safety supervision system and the ''REASON model'' accident cause mechanism, considering the influence of the collusion behavior between enterprise management and front-line staff, a more realistic tripartite evolution game model is built. Secondly, the interaction mechanism of strategy selection among different subjects is discussed and the evolutionary stable equilibrium is analyzed. Thirdly, based on the actual data and interview results, the behavior evolution law of the tripartite subject is revealed by simulation, the relevant parameter control is proposed for guiding the system evolution towards the Pareto optimal direction, so as to improve the risk prevention and control ability. The main contributions of this paper include: more objectively setting the evolutionary game model and simulate the reality from the realizability of the tripartite interest balance; more clearly and completely analyzing the behavior interaction and evolution process of different groups in the achievement of goals in the current railway safety supervision system. It can provide a practical reference for the supervision department.

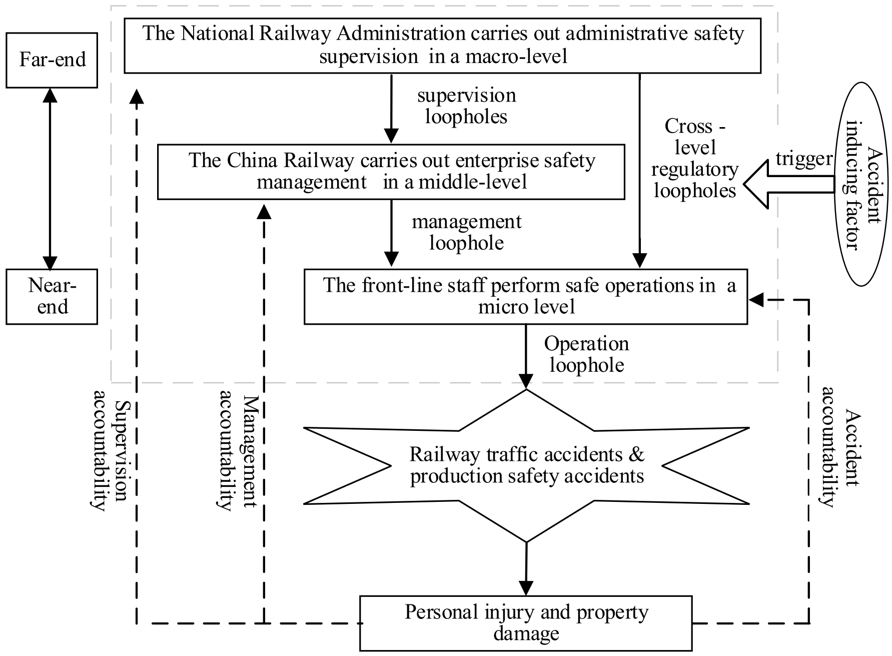


FIGURE 1. Organizational hierarchy of railway safety supervision system and accidental cause mechanism.

II. ORGANIZATIONAL HIERARCHY OF RAILWAY SAFETY SUPERVISION SYSTEM AND ACCIDENTAL CAUSE

The railway safety supervision system is a huge and complex system involving people, society, environment, technology, economy, and politics. Railway accidents are nonlinear, differentiated and aperiodic complex phenomena emerging in the complex system due to the interaction between subject and subject, as well as between subject and environment. According to the ''Reason model'' of Professor James Reason from the University of Manchester in the UK, the accident not only has a reaction chain of the event itself, but also has organization loopholes. The causes of accidents and defects at all levels of the organization evolve by themselves over time. Unsafe factors are like a continuous beam of light. When the beam penetrates the holes at all levels, accidents will occur.

At present, China's railways adopt a safety system of ''key responsibilities of enterprises and government supervision''. The National Railway Administration is a professional supervision organization of the railway industry. It has eight supervision organizations, namely the Beijing Railway Supervision Office and the Regional Railway Administration of Shanghai, Guangzhou, Chengdu, Shenyang, Xi'an, Wuhan and Lanzhou. And they are responsible for administrative supervision enforcement at the level of administrative safety supervision responsibilities. China Railway assume primary responsibility for the whole railway production safety, mainly adopt the mainline management system including the Safety Supervision and Administration Bureau and Special Office of the company, safety supervision department of the company, Safety Branch of station and depot, safety officers of workshop teams. They perform regulatory duties at the level of corporate safety management responsibilities. From the point of the entire operation responsibility system, the production operation layer for front-line staff is near the end of the accident, and the administrative safety supervision layer of the National Railway Administration is at the far end, as well as oversees railway safety together with corporate safety management layer of China Railway (Fig. 1). An accident occurs when all three layers are induced by an accident factor and leak occurs simultaneously or in sequence. In the figure, the solid arrow line represents the positive supervision mechanism and accident cause mechanism between the subjects, while the dotted arrow line represents the reverse accountability mechanism after the accident.

III. BASIC ASSUMPTIONS AND MODEL SPECIFICATION

According to the organizational hierarchy of the railway safety supervision system and the accidental causing mechanism, the model formulation and assumptions for evolutionary game are as follows.

In the game, the agent-sets $i \in \Gamma, \Gamma = (1, 2, 3)$, i.e. $i = 1$ represents player 1, the safety supervision agency of the National Railway Administration, $i = 2$ represents player 2, the China Railway safety management, and $i = 3$ represents player 3, the railway front-line staff. For any player i, strategic space is denoted by S_i $(i = 1, 2, 3)$, the j^{th} $(j = 1, 2)$ strategy adopted is denoted by S_{ij}, and the expectation that player i will receive an expected revenue is U_{ij} $(i = 1, 2, 3,\ j = 1, 2)$. Including, the National Railway Administration's strategy space S_1 is {stringent regulation (S_{11}), superficial supervision (S_{12})}, and the probability of choosing S_{11} is α. The China Railway's strategy space S_2 is {implement safety regulations

TABLE 1. Payment function matrix of railway safety supervision.

Strategies		Safety management layer of China Railway			
		Implement safety regulations in a strict way (S_{21})		Implement safety regulations on the surface (S_{22})	
		Operate according to standard procedures (S_{31})	Operate violating to standard procedures (S_{32})	Operate according to standard procedures (S_{31})	Operate violating to standard procedures (S_{32})
National Railway Administration	Stringent regulation (S_{11})	$-C_g-J_r-J_s+y_g$, $-C_r-J_h+J_r+y_r$, $J_h+J_s+y_s$	$-C_g-J_r+F_s$, $-C_r+F_h+J_r+y_r$, $-F_h-F_s-Z_s+w_s$	$-C_g+F_r-J_s$, $-F_r+F_m-Z_r+w_r$, $-F_m+J_s+y_s$	$-C_g+F_r+F_s$, $-J_m-F_r-Z_r+w_r$, $J_m-F_s-Z_s+w_s$
	Superficial supervision (S_{12})	y_g, $-C_r-J_h+y_r$, y_s+J_h	$-Z_g$, $-C_r+F_h+y_r$, $-F_h-Z_s+w_s$	$-Z_g$, $F_m-Z_r+w_r$, $-F_m+y_s$	$-Z_g$, $-J_m-Z_r+w_r$, $J_m-Z_s+w_s$

Note: The first, second and third items in the matrix respectively represent the payoffs of the National Railway Administration, China Railway safety management and front-line staff.

in a strict way (S_{21}), implement safety regulations on the surface (S_{22})}, and the probability of choosing S_{21} strategy is β. The staff's strategy space is S_3 {operate according to standard procedures (S_{31}), operate violating to standard procedures (S_{32})}, and the probability of choosing S_{31} strategy is γ. The probabilities of choosing opposite strategies are $1-\alpha$, $1-\beta$, $1-\gamma$.

Assumption 1: The probability of a railway accident is a function that depends on the probability of illegal operation by staff and the probability of the safety regulations implementation on the surface by China Railway. And it is not directly related to the supervision intensity of the National Railway Administration.

Assumption 2: The National Railway Administration conducts external supervision on railway safety risks, pays the supervision cost C_g, and gets the political gain y_g (reputation and political achievements) under non-accident. If the National Railway Administration implements superficial supervision, China Railway and staff may superficially implement safety regulations or violate standard operating procedures, which will lead to an increase in accident rates. And according to the reverse accountability mechanism, the National Railway Administration will bear the loss and accident penalties Z_g. In administrative supervision, if the National Railway Administration finds out violations existed in the China Railway and staff, the China Railway and staff will respectively pay F_r and F_s in fines. Otherwise, the China Railway and staff will get awards J_r and J_s respectively.

Assumption 3: Staff obtain the income y_s as they operate according to standard procedures. w_s means the gains of staff (i.e., the cost of energy saved) from breaking the standard procedures. However, at the same time, staff also bear the expected loss and accident penalties Z_s due to an increase in accident rate.

Assumption 4: China Railway costs C_r and obtains benefit y_r when it implement safety regulations in a strict way. If the China Railway implements safety regulations on the surface, it obtains benefit w_r and will bear the loss and accident penalties Z_r. Considering that the management of staff in China Railway belongs to internal management, the "consistency" regulation between staff and management makes it easy for colluding with each other. For example, when it is clear that safe operation conditions are not available, and the management issues an operation order, if the staff accept the order to carry out illegal operation, the management will reward the staff J_m for colluding. Otherwise, management will implement a collusion penalty F_m to the staff. Similarly, management will reward staff J_h for compliance if they strictly follow the SOPs (Standard Operating Procedures, SOPs) under the conditions of safe operation. Otherwise, the management will implement compliance penalty F_h to staff.

According to the above assumptions, the payment matrix of all three in the game is established, as shown in Table 1.

IV. GAME EQUILIBRIUM ANALYSIS

A. EQUILIBRIUM POINT OF EVOLUTION

According to the above assumptions and Table 1, the expected revenues of the positive strategy (stringent regulation S_{11}, implement safety regulations in a strict way S_{21}, and operate according to standard procedures S_{31}) and the negative strategy (superficial supervision S_{12}, implement safety regulations on the surface S_{22}, and operate violating to standard procedures S_{32}) chosen by the three players are respectively:

$$\begin{aligned}U_{11} &= \beta\gamma(-C_g-J_r-J_s+\ y_g)+\beta(1-\gamma)\\ &\quad\times(-C_g-J_r+F_s)+(1-\beta)\gamma(-C_g+F_r-J_s)\\ &\quad+(1-\beta-\gamma+\beta\gamma)(-C_g+F_r+F_s)\\ &= -C_g+F_r+F_s-\beta J_r-\beta F_r-\gamma J_s-\gamma F_s+\beta\gamma y_g \end{aligned} \tag{1}$$

$$\begin{aligned}U_{12} &= \beta\gamma y_g-\beta(1-\gamma)Z_g\\ &\quad-Z_g(1-\beta)\gamma-Z_g(1-\beta-\gamma+\beta\gamma)\\ &= \beta\gamma y_g+\beta\gamma Z_g-Z_g \end{aligned} \tag{2}$$

$$U_{21} = -C_r + F_h + y_r + \alpha J_r - \gamma J_h - \gamma F_h \tag{3}$$
$$U_{22} = -J_m - Z_r + w_r - \alpha F_r + \gamma F_m + \gamma J_m \tag{4}$$
$$U_{31} = -F_m + y_s + \alpha J_s + \beta J_h + \beta F_m \tag{5}$$
$$U_{32} = J_m - Z_s + w_s - \alpha F_s - \beta F_h - \beta J_m \tag{6}$$

According to the Malthusian equation, the replication dynamic equation of the three players can be obtained. Thus a three dimensional dynamic system (I) can be established, i.e.

$$\begin{cases} O = \dfrac{d\alpha}{dt} = \alpha(1-\alpha)(U_{11} - U_{12}) \\ = \alpha(1-\alpha)(-C_g + Z_g + F_r + F_s - \beta J_r - \beta F_r - \gamma J_s \\ -\gamma F_s - \beta\gamma Z_g) \\ M = \dfrac{d\beta}{dt} = \beta(1-\beta)(U_{21} - U_{22}) \\ = \beta(1-\beta)\times \\ (-C_r + Z_r + y_r - w_r + F_h + J_m + \alpha J_r + \alpha F_r \\ -\gamma J_h - \gamma F_h - \gamma F_m - \gamma J_m) \\ N = \dfrac{d\gamma}{dt} = \gamma(1-\gamma)(U_{31} - U_{32}) \\ = \gamma(1-\gamma)\times \\ (y_s + Z_s - w_s - F_m - J_m + \alpha J_s + \alpha F_s + \beta J_h \\ +\beta F_m + \beta F_h + \beta J_m) \end{cases} \tag{7}$$

To facilitate the analysis on the equilibrium point and stability of the system, let

$$\alpha_D = \frac{(e+f)\{Z_g[cg - b(d-e)] + \sqrt{\Delta}\} + 2Z_g b(e+f)(d-e)}{2Z_g bc(e+f)} \in [0,1],$$
$$\beta_D = \frac{2Z_g ab(e+f) - \{Z_g[cg - b(d-e)] + \sqrt{\Delta}\}b}{2Z_g bc(e+f) + \{Z_g[cg - b(d-e)] + \sqrt{\Delta}\}Z_g} \in [0,1],$$
$$\gamma_D = \frac{Z_g[cg - b(d-e)] + \sqrt{\Delta}}{2Z_g b(e+f)} \in [0,1], \quad \beta_E = \frac{g}{e+f} \in [0,1],$$
$$\gamma_E = \frac{e-d}{e+f} \in [0,1], \quad \beta_F = \frac{g-b}{e+f} \in [0,1],$$
$$\gamma_F = \frac{e-d+c}{e+f} \in [0,1], \quad \alpha_G = \frac{g}{b} \in [0,1],$$
$$\gamma_G = \frac{a}{b} \in [0,1], \quad \alpha_H = \frac{g-e-f}{b} \in [0,1],$$
$$\gamma_H = \frac{a-c}{b+Z_g} \in [0,1], \quad \alpha_I = \frac{d-e}{c} \in [0,1],$$
$$\beta_I = \frac{a}{c} \in [0,1], \quad \alpha_J = \frac{d+f}{c} \in [0,1],$$

and $\beta_J = \frac{a-b}{c+Z_g} \in [0,1]$.

In those formulas, $a = -C_g + Z_g + F_r + F_s$, $b = J_s + F_s$, $c = J_r + F_r$, $d = C_r - Z_r - y_r + w_r$, $e = F_h + J_m$, $f = J_h + F_m$, $g = -y_s - Z_s + w_s + F_m + J_m$, and $\Delta = \{Z_g^2(cg - bd + be)^2 - 4Z_g b(e+f)\}(-c^2 g + bcd - bce + cae + caf)$.

Proposition 1: The equilibrium points of system (I) are $(0,0,0)$, $(0,0,1)$, $(0,1,0)$, $(0,1,1)$, $(1,0,0)$, $(1,0,1)$, $(1,1,0)$, $(1,1,1)$. In addition, $(\alpha_D, \beta_D, \gamma_D)$, $(0, \beta_E, \gamma_E)$, $(1, \beta_F, \gamma_F)$, $(\alpha_G, 0, \gamma_G)$, $(\alpha_H, 1, \gamma_H)$, $(\alpha_I, \beta_I, 0)$ and $(\alpha_J, \beta_J, 1)$ are also equilibrium points of the system.

Proof: as for system (I), if let respectively $\frac{d\alpha}{dt} = 0$, $\frac{d\beta}{dt} = 0$, $\frac{d\gamma}{dt} = 0$, then $(0,0,0)$, $(0,0,1)$, $(0,1,0)$, $(0,1,1)$, $(1,0,0)$, $(1,0,1)$, $(1,1,0)$, and $(1,1,1)$ are obviously the equilibrium point of system. When any one of the $(\alpha_D, \beta_D, \gamma_D)$, $(0, \beta_E, \gamma_E)$, $(1, \beta_F, \gamma_F)$, $(\alpha_G, 0, \gamma_G)$, $(\alpha_H, 1, \gamma_H)$, $(\alpha_I, \beta_I, 0)$, $(\alpha_J, \beta_J, 1)$ is substituted in system (I), also $\frac{d\alpha}{dt} = 0$, $\frac{d\beta}{dt} = 0$, $\frac{d\gamma}{dt} = 0$. I.e., 15 partial equilibrium points $E_1 \sim E_{15}$ of system (I) are obtained, and their spatial distribution is shown in Fig. 2.

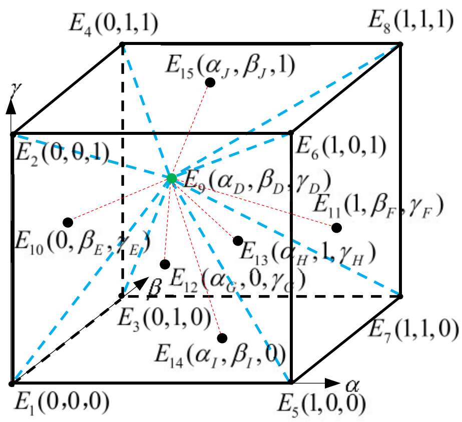


FIGURE 2. **3-D distribution of system equilibrium points.**

B. EQUILIBRIUM POINTS AND ANALYSIS ON THEIR STABILITY

According to the Friedman method, the stability of equilibrium points can be derived from the local stability analysis on the Jacobi matrix J of the system.

$$J = \begin{bmatrix} \dfrac{\partial O}{\partial \alpha} & \dfrac{\partial O}{\partial \beta} & \dfrac{\partial O}{\partial \gamma} \\ \dfrac{\partial M}{\partial \alpha} & \dfrac{\partial M}{\partial \beta} & \dfrac{\partial M}{\partial \gamma} \\ \dfrac{\partial N}{\partial \alpha} & \dfrac{\partial N}{\partial \beta} & \dfrac{\partial N}{\partial \gamma} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \tag{8}$$

In formula (8):

$$a_{11} = (1-2\alpha)(-C_g + Z_g + F_r + F_s - \beta J_r - \beta F_r - \gamma J_s - \gamma F_s - \beta\gamma Z_g),$$
$$a_{12} = \alpha(1-\alpha)(-J_r - F_r - \gamma Z_g), \quad a_{13} = \alpha(1-\alpha) \times (-J_s - F_s - \beta Z_g),$$
$$a_{21} = \beta(1-\beta)(J_r + F_r), \quad a_{22} = (1-2\beta)(-C_r + Z_r + y_r - w_r + F_h + J_m + \alpha J_r + \alpha F_r - \gamma J_h - \gamma F_h - \gamma F_m - \gamma J_m),$$

$$a_{23} = \beta(1-\beta)(-J_h - F_h - F_m - J_m), \quad a_{31} = \gamma(1-\gamma) \times (J_s + F_s),$$

$$a_{32} = \gamma(1-\gamma)(J_h + F_m + F_h + J_m) \quad \text{and } a_{33} = (1-2\gamma) \times (y_s + Z_s - w_s - F_m - J_m + \alpha J_s + \alpha F_s + \beta J_h + \beta F_m + \beta F_h + \beta J_m).$$

From the Jacobi matrix J, the following characteristic equation can be obtained:

$$\det(J - \lambda E) = (a_{11}-\lambda)(a_{22}-\lambda)(a_{33}-\lambda) + a_{21}a_{32}a_{13} + a_{31}a_{23}a_{12} - a_{31}(a_{22}-\lambda)a_{13} - (a_{33}-\lambda)a_{12}a_{21} - a_{32}a_{23}(a_{11}-\lambda) = 0 \quad (9)$$

The root of the characteristic equation (formula (9)) is λ, i.e. the eigenvalue of J. According to Lyapunoy's stability theory [16], if the real components of all eigenvalues are negative, then the system is asymptotically stable at the equilibrium point and the system stability is irrelevant to the higher-order terms. If there is at least one real component of the eigenvalues is positive, then the system is unstable at the equilibrium point and the system cannot reach an evolutionary stable state. If all eigenvalues have positive real components, then the equilibrium point is unstable equilibrium node point (UENP). However, if there are both eigenvalue greater than 0 and eigenvalue less than 0, then the equilibrium point is a saddle point (critical evolutionary stable equilibrium, it is also often regarded as UENP). And if except for the eigenvalue with zero real component, all the other eigenvalues have negative real component, then the stability of the system at the equilibrium point is determined by higher-order terms.

Proposition 2: For the 15 equilibrium points, when any two players respectively adopt the corresponding strategy on a certain equilibrium point, the other one player will change his own strategy if the difference in gains or losses between a positive and a negative strategy changes. Thus, the evolutionary stabilization strategy will change.

Proof: To substitute the 15 equilibrium points into formula (9), according to the sign of the real component of the eigenvalue λ, to analyze local stability of 15 equilibrium point of the evolution system (I) under different restrictive conditions.

① For the equilibrium points $E_1 \sim E_8$, if the three eigenvalues of the Jacobi matrix J are all less than 0, then the equilibrium point is the evolutionary stable point of the system, and the corresponding strategy is the ESS (Evolutionarily Stable Strategy) of system (I).

Taking equilibrium point $E_1(0,0,0)$ as an example, when the eigenvalues $\lambda_1 = -C_g + Z_g + F_r + F_s < 0$, $\lambda_2 = -C_r + Z_r + y_r - w_r + F_h + J_m < 0$, $\lambda_3 = y_s + Z_s - w_s - F_m - J_m < 0$, $E_1(0,0,0)$ is the evolutionary stable point of the system. I.e., the ESS is (S_{12}, S_{22}, S_{32}).

As table 1 show, $-C_g + Z_g + F_r + F_s$ is the difference in the gains of the National Railway Administration between the positive strategy S_{11} and the negative strategy S_{12} when the Chinese Railway adopts the negative strategy S_{22} and staff adopt the negative strategy S_{32}. $-C_r + Z_r + y_r - w_r + F_h + J_m$ is the difference in the gains of the China Railway between the positive strategy S_{21} and the negative strategy S_{22} when the National Railway Administration adopts the negative strategy S_{12} and staff adopt the negative strategy S_{32}. $y_s + Z_s - w_s - F_m - J_m$ is the difference in the gains of staff between the positive strategy S_{31} and the negative strategy S_{32} when the National Railway Administration adopts negative strategy S_{12} and the Chinese Railway adopts negative strategy S_{22}. It can be seen that whether $E_1(0,0,0)$ has evolutionary stability depends on the plus or minus sign of the difference in the above-mentioned gains. If all the three adopt the positive strategy to get less income than the one under the negative strategy, $E_1(0,0,0)$ will have evolutionary stability. Similar to the analysis of the equilibrium point E_1, according to table 1, all the eigenvalues λ_1, λ_2 and λ_3 of the Jacobi matrix at $E_2 \sim E_8$ (For detailed data, see the table 2) correspond to the difference (or the opposite number) in the gains of the player between the positive strategy and the negative strategy when other two players respectively adopt the corresponding strategy on a certain equilibrium point. When λ_1, λ_2 and λ_3 are all less than 0, the corresponding equilibrium point is the evolutionary stable point of the system. Obviously, whether $E_2 \sim E_8$ has evolutionary stability also depends on the plus or minus sign of the difference in the gains. Under bounded rationality, when the expected revenue from the implementation of a positive strategy is higher than that from the implementation of negative strategy, the subject will be inclined to choose the positive strategy, otherwise choose the implementation of negative strategy.

② For the equilibrium point E_9, when $\alpha = \alpha_D$, $\beta = \beta_D$, and $\gamma = \gamma_D$ are substituted into formula (9), the characteristic root is the solution of a cubic algebraic equation $-\lambda^3 - \lambda\xi + \varsigma = 0$. In the cubic algebraic equation, $\varsigma = \alpha_D(1-\alpha_D)\beta_D(1-\beta_D)\gamma_D(1-\gamma_D)(e+f)Z_g(-c\beta_D + b\gamma_D)$, $\xi = \alpha_D(1-\alpha_D)\gamma_D(1-\gamma_D)(b^2 + \beta_D bZ_g) + \alpha_D(1-\alpha_D)\beta_D(1-\beta_D)(c^2 + \gamma_D cZ_g) + \beta_D(1-\beta_D)\gamma_D(1-\gamma_D)(e+f)$. Obviously, if $\varsigma \neq 0$, there are no zero roots of the equation. And for any complex number with a zero real component $0 + i\tau$, substituting it into the left of $-\lambda^3 - \lambda\xi + \varsigma = 0$, then $-\lambda^3 - \lambda\xi + \varsigma = (\tau^3 - \tau\xi)i + \varsigma \neq 0$. So the characteristic equation has no root with zero real component. According to the description of n-th order algebraic equations with constant coefficients in the Hurwitz criterion, if the coefficient of the quadratic term in the cubic algebraic equation is 0, then the cubic algebraic equation has roots with positive real component. Therefore, when $\varsigma \neq 0$, $(\alpha_D, \beta_D, \gamma_D)$ is not asymptotically stable.

Also according to Table 1, the sub-items of all elements in the Jacobi matrix $a_{11}, a_{12}, \ldots, a_{33}$ at the equilibrium point E_9, such as $C_r - Z_r - y_r + w_r - F_h - J_m$, $y_s + Z_s - w_s - F_m - J_m$, $-C_g + Z_g + F_r + F_s$, $J_s + F_s$, $J_r + F_r$, $F_h + J_m$, $J_h + F_m$ and Z_g. The strategy adopted by certain a player has also been associated with the difference in gains or losses of the player between a positive and a negative strategy, when the other two players respectively adopt the corresponding strategy on equilibrium point $E_9(\alpha_D, \beta_D, \gamma_D)$.

③ For the equilibrium point $E_{10} \sim E_{15}$, similar to the analysis of the equilibrium point E_9, the corresponding values of α, β, γ of the equilibrium points $E_{10}(0, \beta_E, \gamma_E)$, $E_{11}(1, \beta_F, \gamma_F)$, $E_{12}(\alpha_G, 0, \gamma_G)$, $E_{13}(\alpha_H, 1, \gamma_H)$, $E_{14}(\alpha_I, \beta_I, 0)$, $E_{15}(\alpha_J, \beta_J, 1)$ will be substituted into the Jacobi matrix formula, and their characteristic root λ is the solution of the cubic algebraic equation. According to the Italian scholar Cardano [17], any standard cubic equation with one unknown quantity can be transformed into the form of $-\lambda^3 - \lambda\phi + \varphi = 0$ (Coefficients ϕ and φ are corresponding complex expressions. Here, only the value case of the root is analyzed. They do not need to be listed.). Therefore, for the equilibrium point $E_{10} \sim E_{15}$, the characteristic roots of the Jacobi matrix under the corresponding values of α, β, γ are the solutions of the cubic algebraic equation $-\lambda^3 - \lambda\phi + \varphi = 0$. Similarly, when $\varphi \neq 0$, the cubic algebraic equation has roots with positive real component. I.e., the $E_{10} \sim E_{15}$ are not asymptotically stable, and the corresponding combination of strategies are unstable.

Similarly, the sub-items of all elements in the Jacobi matrix $a_{11}, a_{12}, \ldots, a_{33}$ at the equilibrium points $E_{10} \sim E_{15}$ have also been associated with the difference in gains or losses of the player between a positive and a negative strategy, when the other two players respectively adopt the corresponding strategy.

In summary, proposition 2 is correct. The stability of all equilibrium points of system (I) is shown in Table 2.

C. ANALYSIS ON THE EVOLUTIONARY STABILITY OF THE THREE GAME-AGENTS UNDER DIFFERENT PARAMETER

If the derivative of this first expression of 3-D dynamic system (I) (formula (7)) is taken, it will be obtained as follow.

$$\frac{\partial O}{\partial \alpha} = (1 - 2\alpha)(-C_g + Z_g + F_r + F_s - \beta J_r - \beta F_r - \gamma J_s - \gamma F_s - \beta\gamma Z_g) \quad (10)$$

① When $-C_g + Z_g + F_r + F_s - \beta J_r - \beta F_r - \gamma J_s - \gamma F_s - \beta\gamma Z_g = 0$, and let $O(\alpha) \equiv 0$, it can be known that system is in a stable state for α arbitrary value.

② When $-C_g + Z_g + F_r + F_s - \beta J_r - \beta F_r - \gamma J_s - \gamma F_s - \beta\gamma Z_g \neq 0$, and let $O(\alpha) \equiv 0$, it can be known that $\alpha = 0$ and $\alpha = 1$ are the two stable states of α.

According to the character of evolutionary stability, if $\frac{\partial O(\alpha^*)}{\partial \alpha}|_{\alpha=\alpha^*} < 0$, α^* is the evolutionary stability strategy. And if $-C_g+Z_g+F_r+F_s-\beta J_r-\beta F_r-\gamma J_s-\gamma F_s-\beta\gamma Z_g > 0$, then when $\frac{\partial O(\alpha)}{\partial \alpha}|_{\alpha=1} < 0$ and $\frac{\partial O(\alpha)}{\partial \alpha}|_{\alpha=0} > 0$, $\alpha = 1$ is the equilibrium point of evolution. If $-C_g+Z_g+F_r+F_s-\beta J_r-\beta F_r-\gamma J_s-\gamma F_s-\beta\gamma Z_g < 0$, then when $\frac{\partial O(\alpha)}{\partial \alpha}|_{\alpha=1} > 0$ and $\frac{\partial O(\alpha)}{\partial \alpha}|_{\alpha=0} < 0$, $\alpha = 0$ is the equilibrium point of evolution.

It can be seen that whether the National Railway Administration implements a stringent regulation strategy is related to the profit difference between the positive and negative strategy adopted by the China Railway safety management and staff with probability a probability of β, γ or $1-\beta, 1-\gamma$.

TABLE 2. Stability analysis of equilibrium points.

Equilibrium point	The eigenvalue case of J	Stability
$E_1\ (0,0,0)$	$\lambda_1=-C_g+Z_g+F_r+F_s<0$ $\lambda_2=-C_r+Z_r+y_r-w_r+F_h+J_m<0$ $\lambda_3=y_s+Z_s-w_s-F_m-J_m<0$	Stable (ESS)
$E_2\ (0,0,1)$	$\lambda_1=-C_g+F_r-J_s+Z_g<0$ $\lambda_2=Z_r-F_m-J_h-C_r-w_r+y_r<0$ $\lambda_3=-y_s-Z_s+w_s+F_m+J_m<0$	Stable (ESS)
$E_3\ (0,1,0)$	$\lambda_1=-C_g+Z_g+F_s-J_r<0$ $\lambda_2=C_r-F_h-J_m-Z_r+w_r-y_r<0$ $\lambda_3=y_s+Z_s-w_s+J_h+F_h<0$	Stable (ESS)
$E_4\ (0,1,1)$	$\lambda_1=-C_g-J_r-J_s<0$ $\lambda_2=C_r+F_m+J_h-Z_r+w_r-y_r<0$ $\lambda_3=w_s-J_h-Z_s-F_h-y_s<0$	Stable (ESS)
$E_5\ (1,0,0)$	$\lambda_1=C_g-F_r-F_s-Z_g<0$ $\lambda_2=F_h-C_r+F_r+J_m+J_r+Z_r-w_r+y_r<0$ $\lambda_3=F_s-F_m-J_m+J_s+Z_s-w_s+y_s<0$	Stable (ESS)
$E_6\ (1,0,1)$	$\lambda_1=C_g-F_r+J_s-Z_g<0$ $\lambda_2=F_r-F_m-C_r-J_h+J_r+Z_r-w_r+y_r<0$ $\lambda_3=F_m-F_s+J_m-J_s-Z_s+w_s-y_s<0$	Stable (ESS)
$E_7\ (1,1,0)$	$\lambda_1=C_g-F_s+J_r-Z_g<0$ $\lambda_2=C_r-F_h-F_r-J_m-J_r-Z_r+w_r-y_r<0$ $\lambda_3=F_h+F_s+J_h+J_s+Z_s-w_s+y_s<0$	Stable (ESS)
$E_8\ (1,1,1)$	$\lambda_1=C_g+J_r+J_s<0$ $\lambda_2=C_r+F_m-F_r+J_h-J_r-Z_r+w_r-y_r<0$ $\lambda_3=w_s-F_s-J_h-J_s-Z_s-F_h-y_s<0$	Stable (ESS)
$E_9\ (\alpha_D,\beta_D,\gamma_D)$	The characteristic equation has neither zeroes roots nor roots with zero real component.	Center point, unstable
$E_{10}\ (0,\beta_E,\gamma_E)$	The characteristic equation has neither zeroes roots nor roots with zero real component.	Saddle point, unstable
$E_{11}\ (1,\beta_F,\gamma_F)$	The characteristic equation has neither zeroes roots nor roots with zero real component.	Saddle point, unstable
$E_{12}\ (\alpha_G,0,\gamma_G)$	The characteristic equation has neither zeroes roots nor roots with zero real component.	Saddle point, unstable
$E_{13}\ (\alpha_H,1,\gamma_H)$	The characteristic equation has neither zeroes roots nor roots with zero real component.	Saddle point, unstable
$E_{14}\ (\alpha_I,\beta_I,0)$	The characteristic equation has neither zeroes roots nor roots with zero real component.	Saddle point, unstable
$E_{15}\ (\alpha_J,\beta_J,1)$	The characteristic equation has neither zeroes roots nor roots with zero real component.	Saddle point, unstable

The dynamic trend and stability of the National Railway Administration are shown in Fig. 3. Similarly, those of China Railway safety management and staff are shown in Fig. 4 and Fig. 5 respectively.

V. CASE ANALYSIS AND NUMERICAL CALCULATION

By looking through the public 2018 departmental accounts of National Railway Administration of the People's Republic

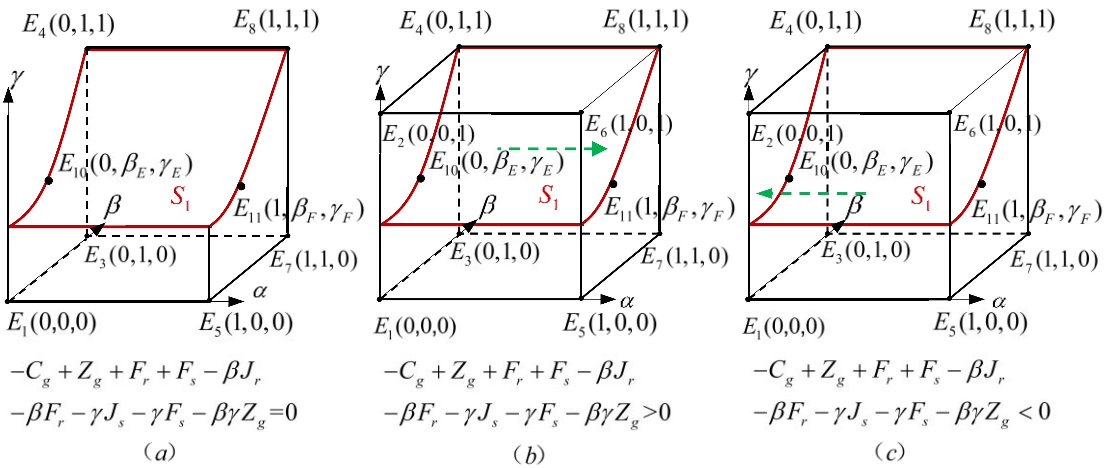


FIGURE 3. Dynamic trend diagram of national railway administration.

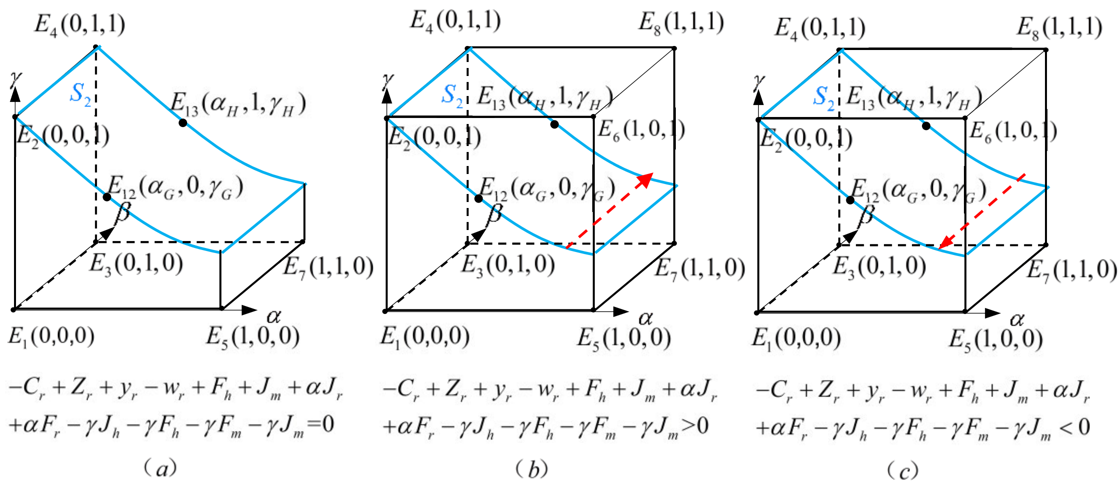


FIGURE 4. Dynamic trend diagram of china railway safety management.

of China (including various revenue data such as fiscal appropriation revenue, grant from the higher authority, undertaking revenue, operating revenue, revenue from the auxiliary organization, etc.; various expenditure data such as social security and employment spending, transportation expenditure, health care and family planning expenditures, Housing security expenditure, etc.) [18], the 2018 Railway Safety Announcement (2019) [19], the operational practice research and estimation of China Railway (including various income data such as revenue from general public budget appropriations, revenue from budgetary appropriations for government-managed funds, grant from the higher authority, undertaking revenue, operating revenue, etc.; various expenditure data such as defense expenditure, public security expenditure, social security and employment spending, transportation expenditure, employee wage expenses, etc.; as well as the commissioning status, construction situation, internal reward and punishment mechanism of the enterprise), as well as referencing to industry expert opinions, the values of parameters are shown in Table 3.

For railway safety supervision, the ideal state is that the system evolves to equilibrium state. That is, railway staff consciously operate according to standard procedures, China Railway implements safety regulations in a strict way and the National Railway Administration does not need to implement a stringent regulation. From the perspective of model solving, only the key variables that affect the behavior probability of all parties can be pinpointed, and the corresponding measures can be taken in practice to increase the probability of all parties implementing ideal behaviors. Ultimately, the risk management and control capability of railway supervision system can be improved.

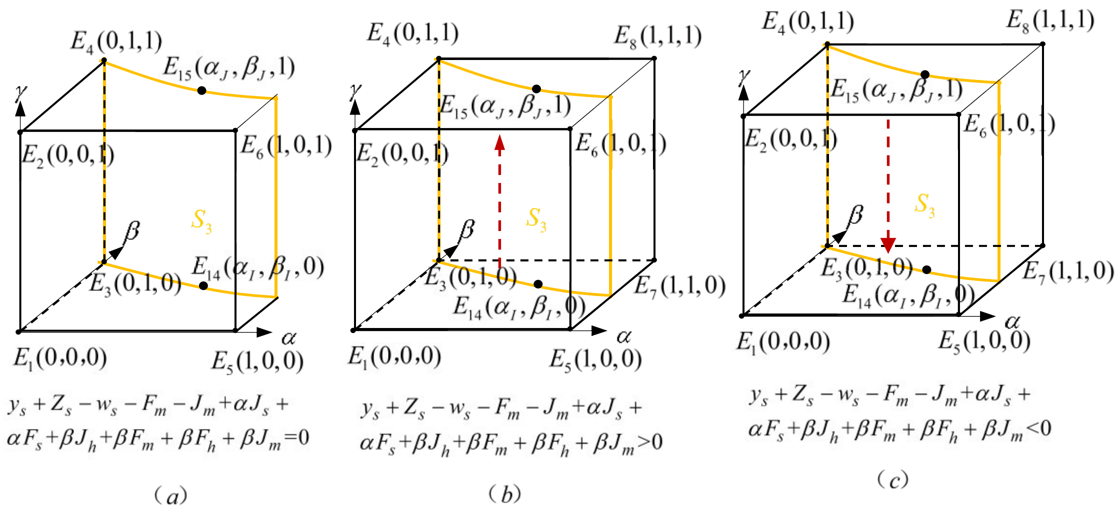


FIGURE 5. Dynamic trend diagram of railway worker at the production line.

TABLE 3. Railway safety data of china in 2018 (unit: 10 thousand yuan).

Parameter	Meaning	Value
C_g	The National Railway Administration pays the regulatory costs	14042.77
y_g	The political gain of the National Railway Administration when there is no accident	30000
Z_g	The National Railway Administration implements superficial supervision and bears later accountability punishment of accident	15000
F_r	The National Railway Administration imposes punishment on China railway for violation	3567.94
F_s	The National Railway Administration imposes punishment on the staff for violation	2000
J_r	The National Railway Administration rewards China railway for compliance	1500
J_s	The National Railway Administration rewards the staff for compliance	1000
y_s	Benefits obtained from the compliance production of the staff	12000000
w_s	Benefits obtained from illegal production by the staff	5000000
Z_s	Illegal production accident accountability punishment to the staff	1500
C_r	The China Railway pays the regulatory costs	1472282
y_r	China Railway's benefits from the safety regulations in a strict way	106580000
w_r	China Railway's benefits from the safety regulations on the surface	50000000
Z_r	China Railway bears accountability punishment for accident	50000
J_m	China Railway rewards the staff for collusion	2000
F_m	China Railway penalizes the staff for conspiracy	2500
J_h	China Railway rewards the staff for compliance	4320
F_h	China Railway penalizes the staff for compliance	5500

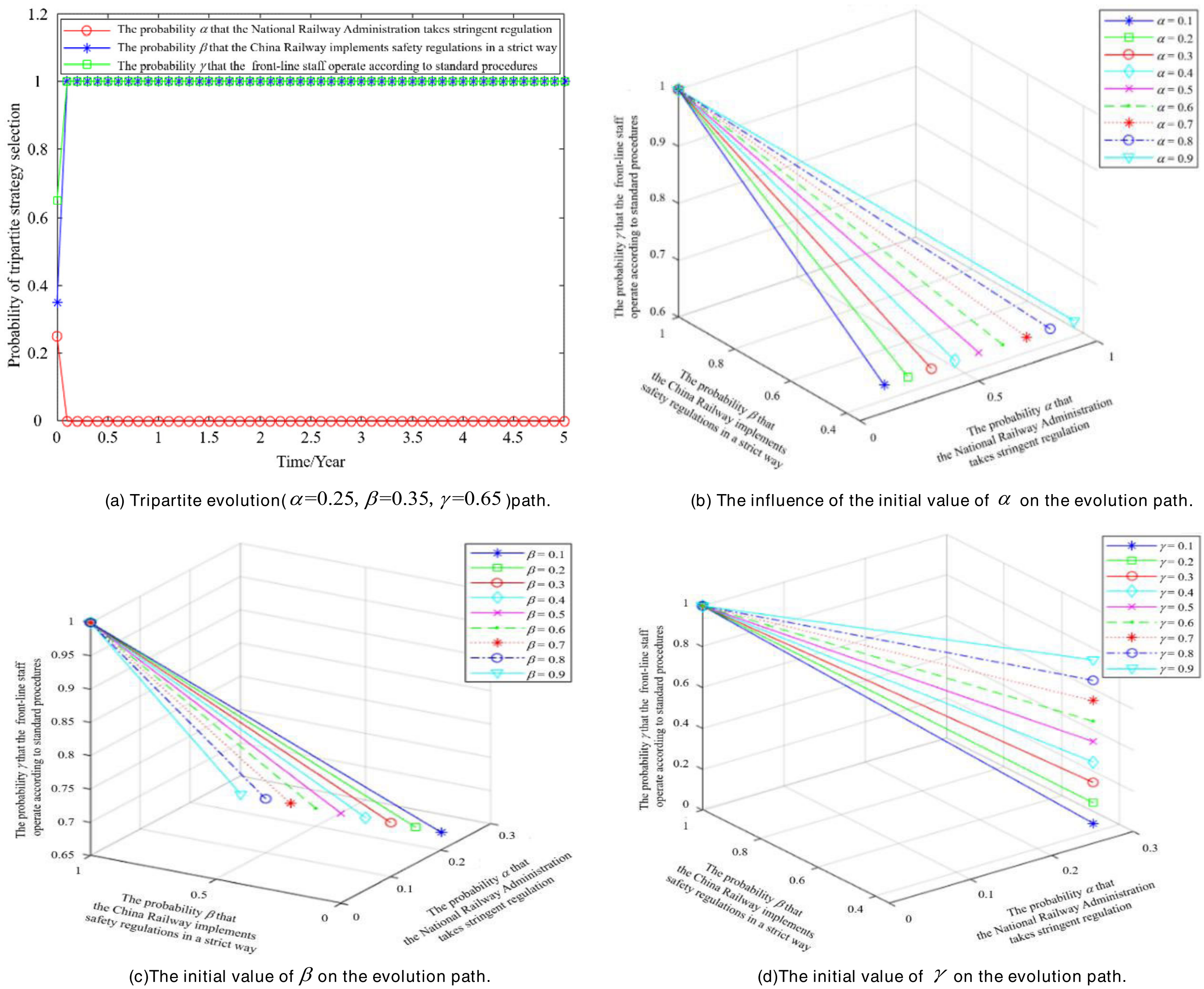
A. THE INFLUENCE OF THE INITIAL PROBABILITY VALUE OF STRATEGY SELECTION ON THE EVOLUTION PATH

Substituting the data of Table 3 into Table 2 and analyzing the stability of the equilibrium point of system (I), the eigenvalues of Jacobi matrix at equilibrium point $E_4(0, 1, 1)$ are $\lambda_1 = -16542.77$, $\lambda_2 = -55150898 < 0$, $\lambda_3 = -7011320 < 0$, so $E_4(0, 1, 1)$ is the evolutionary stability strategy of the system. For discussing the influence of the initial probability value of strategy selection on the evolution path, Four scenarios are set for simulation: ① $\alpha = 0.25$, $\beta = 0.35$, $\gamma = 0.65$; ② $\beta = 0.35, \gamma = 0.65$ and the value range of α is 0.1∼0.9; ③ $\alpha = 0.25$, $\beta = 0.35$ and the value range of γ is 0.1∼0.9; ④ $\alpha = 0.25$, $\gamma = 0.65$ and the value range of β is 0.1∼0.9. The equilibrium point of system (I) is $E_4(0, 1, 1)$, and the evolution process is shown in Fig. 6(a), (b), (c) and (d).

From Fig. 6(a)∼6(d), it can be seen that under the guidance of the current policy, even if the initial value change of α, β and γ, the system will eventually reach the ideal state through tripartite evolution, and eventually realize the Pareto optimal equilibrium of the game. It shows that the current policy and management system are in a scientific and reasonable category. This result is in line with China being one of transportation powerful country with larger railway operation scale, comprehensive technology, abundant management experience and perfect management system in the world. China has stepped into the world's leading ranks in railway safety supervision system. According to the Railway Safety Bulletin 2019, the current mortality rate of 1 billion ton-km of China's railways is 0.173, maintaining the lowest casualty rate worldwide [20]. This result in Fig. 6(a)∼6(d) is also consistent with the good status of Railway safety in China.

B. THE PATH EVOLVES WITH THE CHANGE OF THE NATIONAL RAILWAY ADMINISTRATION'S SOME PARAMETERS AND THE STAFF'S COLLUSION REWARDS AND ACCOUNTABILITY IN PAYOFF MATRIX

While the other parameters in Table 3 remain the same, only the National Railway Administration changed its payment for regulatory costs C_g (or only the National Railway Administration changed its rewards J_r for compliance



(a) Tripartite evolution(α=0.25, β=0.35, γ=0.65)path.

(b) The influence of the initial value of α on the evolution path.

(c)The initial value of β on the evolution path.

(d)The initial value of γ on the evolution path.

FIGURE 6. The tripartite evolution process and the influence of the initial probability on the evolution path.

behavior of China Railway, or only the National Railway Administration changed its rewards J_s for compliance behavior of staff), According to the Jacobi matrix eigenvalue calculation formula at the equilibrium point $E_4(0, 1, 1)$, it can be known that no matter what non-negative number C_g (or J_r, J_s) is, always $\lambda_1 = -C_g - J_r - J_s < 0$. And since C_g (or J_r, J_s) is not included in the formulas, its value does not affect the operation result of λ_2 and λ_3. So, as long as the value of C_g (or J_r, J_s) is non-negative, the evolutionary stability strategy of the system is (0, 1, 1).

In the same way, it is found that the National Railway Administration's political gain y_g, accountability punishment Z_g, punishments F_r and F_s given to China Railways and staff, the collusion rewards J_m and the accountability Z_s given to staff are not included in the formulas of λ_1, λ_2 and λ_3 of the Jacobi matrix at the equilibrium point $E_4(0, 1, 1)$, So in the current situation, while the other parameters values in Table 3 remain the same, changing only one parameter in y_g, Z_g, F_r, F_s and J_m does not affect the stable condition of the equilibrium point $E_4(0, 1, 1)$. The system will still evolve to the equilibrium state (0, 1, 1), and the Pareto optimal equilibrium of the three-party evolutionary game is realized. This is because the model construction is based on the premise that if and only if Chinese railway and staff adopt negative strategies at the same time, railway accidents will occur. As long as these parameters are non-negative, the system evolution is stable at (0, 1, 1). Due to space limitation and similar evolution process, $\alpha = 0.25$, $\beta = 0.35$ and $\gamma = 0.65$ are set. Fig. 7 only lists the influence of J_m change on the evolution path.

C. PATH EVOLVES WITH THE CHANGE OF THE CHINA RAILWANY'S REGULATORY COSTS, BENEFITS AND COMPLIANCE REWARD

Only changing the value of C_r, the evolution result is shown in Fig. 8. It can be seen from Fig. 8 that there are two

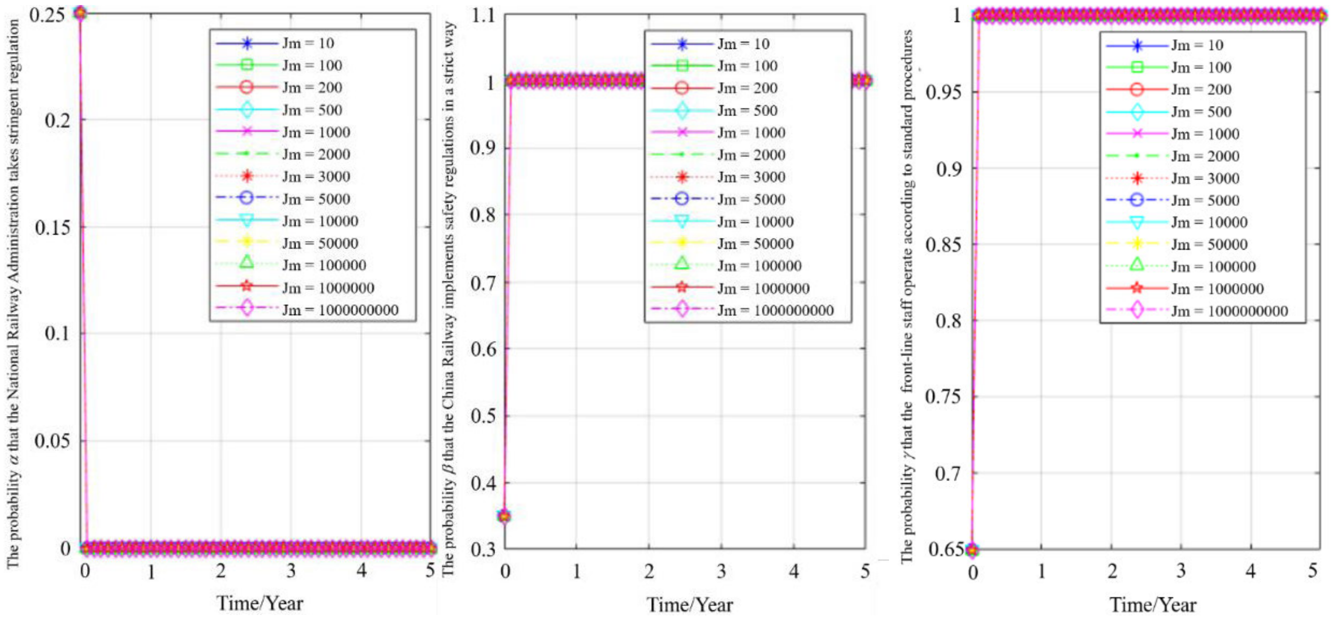


FIGURE 7. **The influence of china railway's collusion reward for staff on the evolutionary path.**

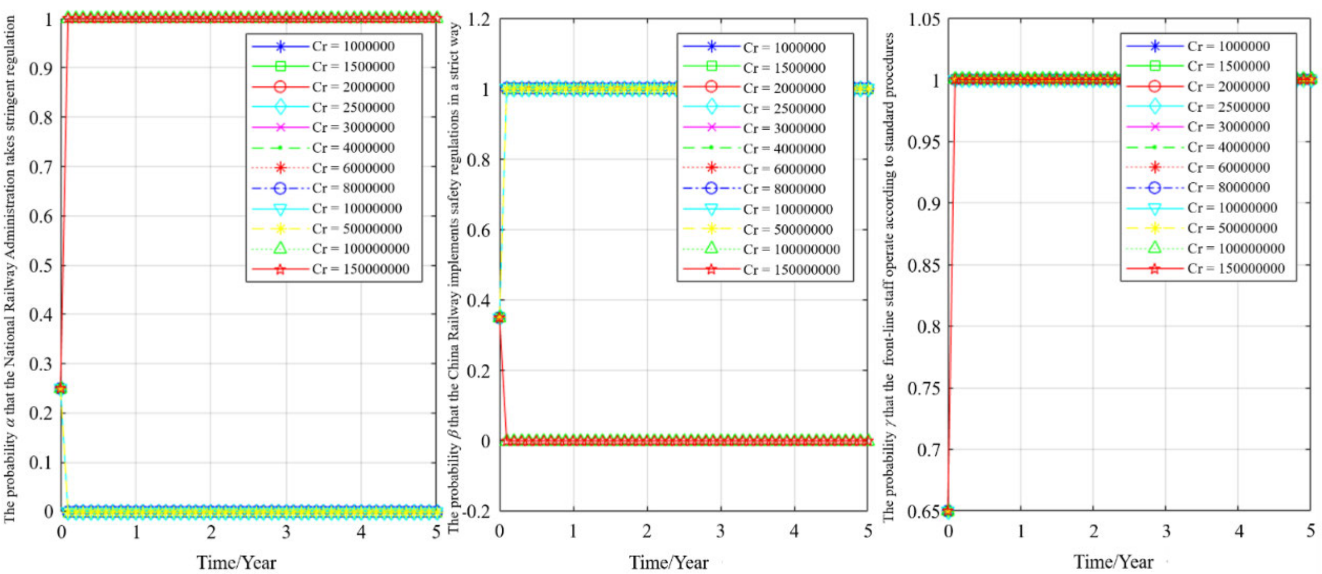


FIGURE 8. **The impact of the cost of china railways' supervision of staff on the evolution.**

equilibrium outcomes: (0, 1, 1) and (1, 0, 1). Concrete analysis is as follows: ① No matter what the value of C_r is, γ always evolves to 1. That is, the staff adopt positive strategies. ② With the value increase of C_r($C_r > 56623180$), β evolves from 1 to 0. I.e., because of the cost increase of regulatory supervision, China Railway will be much less willing to choose safety regulations in a strict way, and then it chooses the negative strategy. ③ With the value increase of C_r, α evolves from 0 (when $C_r < 56623180$, the eigenvalues λ_2 of Jacobi matrix at equilibrium point $E_4(0, 1, 1)$ is less than 0), to 1 (when $C_r > 56628247.94$, the eigenvalues λ_2 of Jacobi matrix at equilibrium point $E_6(1, 0, 1)$ is less than 0). This is because when C_r is larger, China Railway has less willingness to choose positive strategies. It leads to the fact that National Railway Administration must choose strict supervision, so as to urge China Railway to implement safety regulations in a strict way and avoid accidents. Under these circumstances, the staff still choose to operate according to standard procedures. Therefore, in order to reach the Pareto optimal state (0, 1, 1) in the two equilibrium points, the value of C_r cannot be set too large.

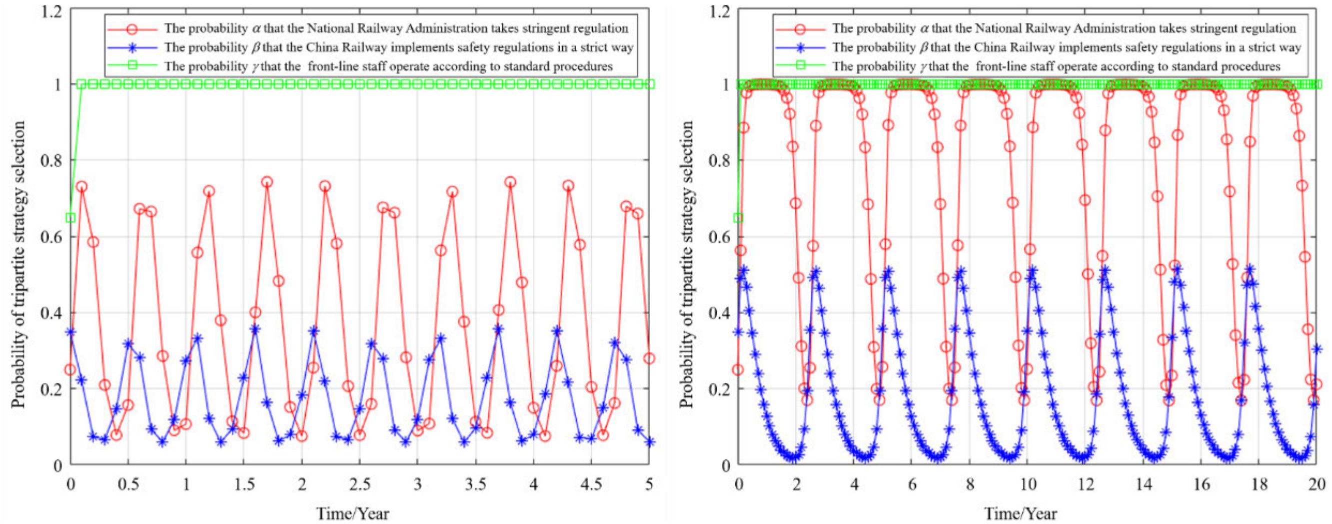


FIGURE 9. The game evolution process fluctuates (left figure $C_r = 56625000$, right figure $y_r = 51425000$).

From the perspective of dynamic game in economics, the jump of equilibrium point from one state to another is a trade-off between cost and strategy choice, which indicates the strategic dependence and mutual constraint between a certain subject's own cost input and other subject's cost input in the game, and also exactly confirms the proposition 2 proposed in this paper.

In the same way, only changing the value of y_r or J_h, the result and process of evolutionary equilibrium are similar to that in Fig. 8, so the evolutionary diagram is omitted.

Concrete analysis is as follows: as for the regulated revenue of China Railway, ① No matter what the value of y_r is, γ always evolves to 1. That is, the staff adopt positive strategies. ② With the value of y_r decreasing ($y_r < 51429102$), β evolves from 1 to 0. I.e., due to the benefits decrease of regulations in a strict way, China Railway will be much less willing to choose positive strategy, and then it chooses regulations on the surface. ③ With the value of y_r decreasing, α evolves from 0 (when $y_r > 51429102$, the eigenvalues λ_2 of Jacobi matrix at equilibrium point $E_4(0, 1, 1)$ is less than 0),to 1 (when $y_r < 51424034.06$, the eigenvalues λ_2 of Jacobi matrix at equilibrium point $E_6(1, 0, 1)$ is less than 0). This is because when y_r is smaller, it is easy to frustrate the enthusiasm of enterprises to actively participate in supervision and create compliance production conditions for front-line staff, China Railway has less willingness to choose positive strategies. It leads to the fact that National Railway Administration must choose strict supervision, so as to urge China Railway to implement safety regulations in a strict way and avoid accidents.

Under these circumstances, the staff still choose positive strategy. Therefore, in order to reach the Pareto optimal state (0, 1, 1) in the two equilibrium points, the value of y_r cannot be set too small.

For China Railway to give frontline staff compliance rewards, ① No matter what the value of J_h is, γ always evolves to 1. That is, the staff adopt positive strategies. ② With the value increase of J_h($J_h > 55155218$), β evolves from 1 to 0. I.e., due to the payments increase of regulations in a strict way, China Railway will be much less willing to choose positive strategy, and then it chooses regulations on the surface. ③ With the value increase of J_h, α evolves from 0 (when $J_h < 55155218$, the eigenvalues λ_2 of Jacobi matrix at equilibrium point $E_4(0, 1, 1)$ is less than 0),to 1 (when $J_h > 55160285.94$, the eigenvalues λ_2 of Jacobi matrix at equilibrium point $E_6(1, 0, 1)$ is less than 0). This is because when J_h is larger, if China Railway adopts a negative strategy, the National Railway Administration must choose strict supervision to ensure railway operation and production safety. Therefore, in order to reach the Pareto optimal state (0, 1, 1) in the two equilibrium points, the value of J_h cannot be set too large.

In order to further observe the game evolution fluctuate caused by the value change of C_r, y_r and J_h, other parameters values of the system are fixed. Four scenarios are set for simulation: ① $C_r = 56625000$; ② $y_r = 51425000$; ③ $J_h = 55160000$; ④ $J_h = 55155300$. Since in scenarios ① (figure 9, left), $56623180 < C_r < 56628247.94$ and in scenarios ② (Fig. 9, right), $51424034.06 < y_r < 51429102$, there is no stable equilibrium point in the two scenarios. China railway selection probability of positive strategy is constantly changing, the game is in periodic turbulence state, there is no stable evolution result. Thus it may cause safety accidents to occur sporadically and intermittently. In scenarios ③ and ④, $55155218 < J_h < 55160285.94$, so there is no stable equilibrium point. China railway selection probability of a positive strategy presents a short - term damped oscillation. Which value α or β converges to depend on the value of J_h. When $J_h = 55156000$, it converges to the

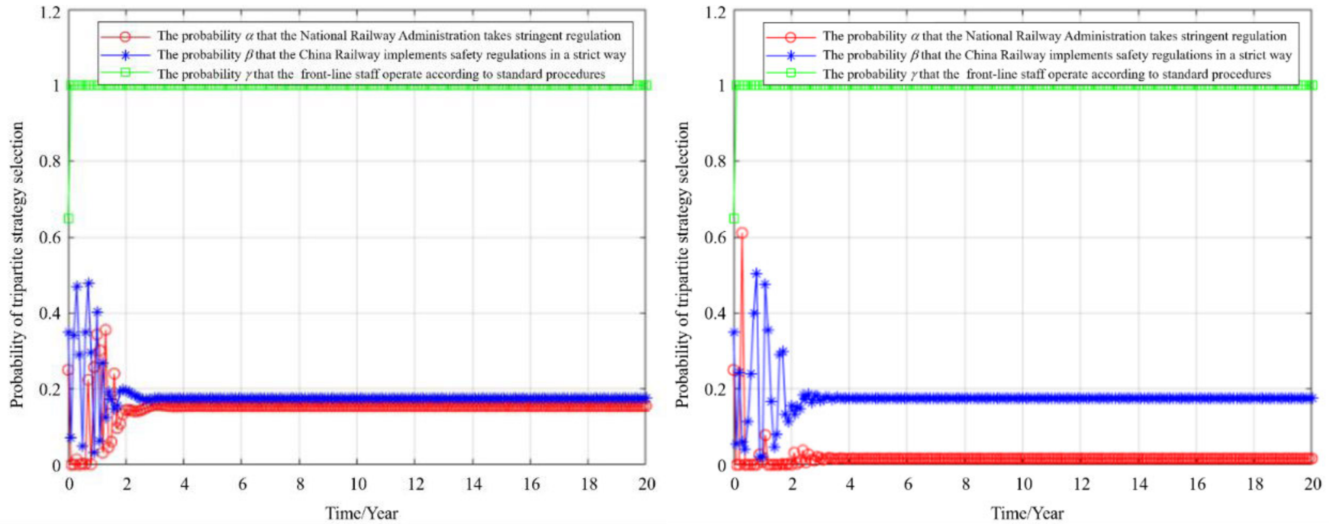


FIGURE 10. The game evolution process fluctuates (left: $J_h = 55156000$ and right: $J_h = 55155300$).

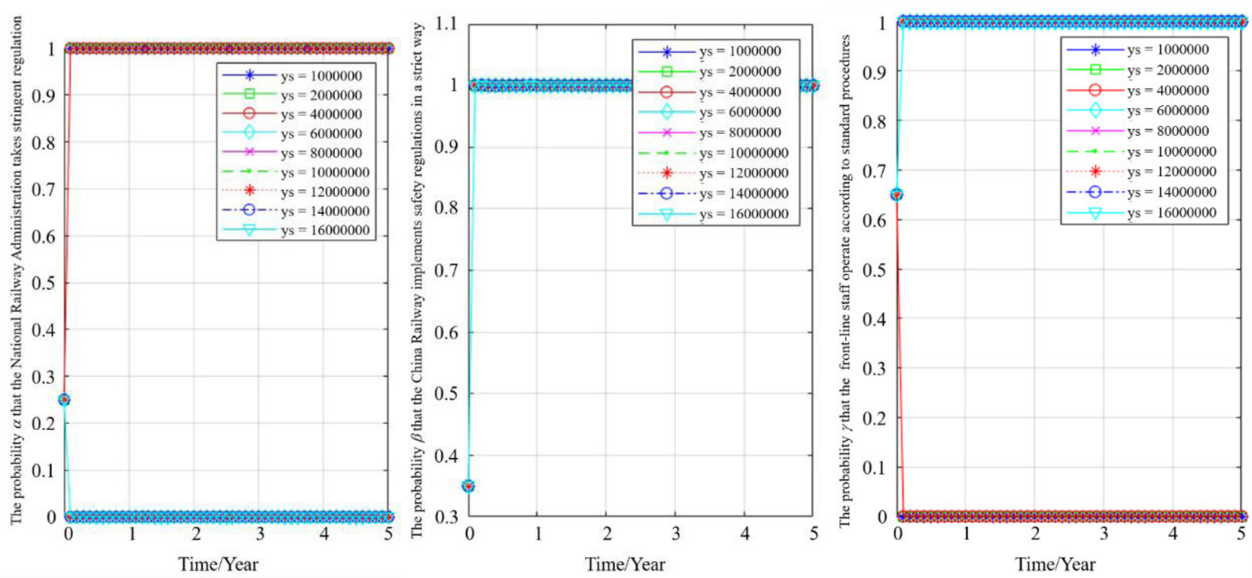
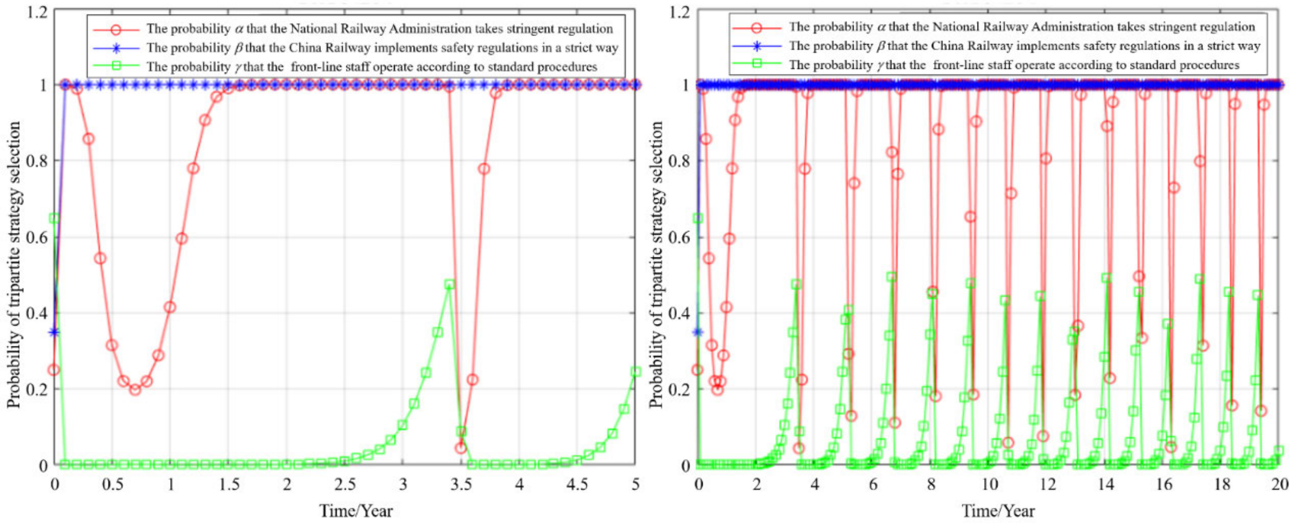


FIGURE 11. The impact of the benefits of compliance production by railway front-line staff on evolution.

equilibrium point (0.1543, 0.1757, 1), as showed in Fig. 10, left. When $J_h = 55155300$, it converges to the equilibrium point (0.0162, 0.1757, 1), as showed in Fig. 10, right.

D. THE INFLUENCE OF THE STAFF'S BENEFITS FROM COMPLIANCE PRODUCTION ON THE EVOLUTION PATH

Only changing the value of y_s, the evolution result is shown in Fig. 11. It can be seen from Fig. 11 that there are two equilibrium outcomes: (1, 1, 0) and (0, 1, 1). I.e., ① No matter what the value of y_s is, β always evolves to 1. That is, the China Railway adopts positive strategy. ② With the value increase of y_s, γ evolves from 0 to 1. I.e., that is, when the income obtained by compliance production becomes larger, it will be motivated by the growth of personal income (when $y_s > 4988680$). And it promotes the enthusiasm of frontline staff for compliance production and then increases their willingness to operate according to standard procedures. ③ With the value increase of y_s, α evolves from 1 (when $y_s < 4985680$, the eigenvalues λ_3 of Jacobi matrix at equilibrium point $E_7(1, 1, 0)$ is less than 0), to 0 (when $y_s > 4988680$, the eigenvalues λ_3 of Jacobi matrix at equilibrium point $E_4(0, 1, 1)$ is less than 0). This is because when y_s is larger, the National Railway Administration does not have to choose stringent regulation and can still guarantee system safety when China Railway has implemented safety regulations in a strict way and front-line staff have operated according to



(a) 5 years of Evolutionary Game.

(b) 20 years of Evolutionary Game.

FIGURE 12. $y_s = 4986000$, **tripartite evolutionary game fluctuates.**

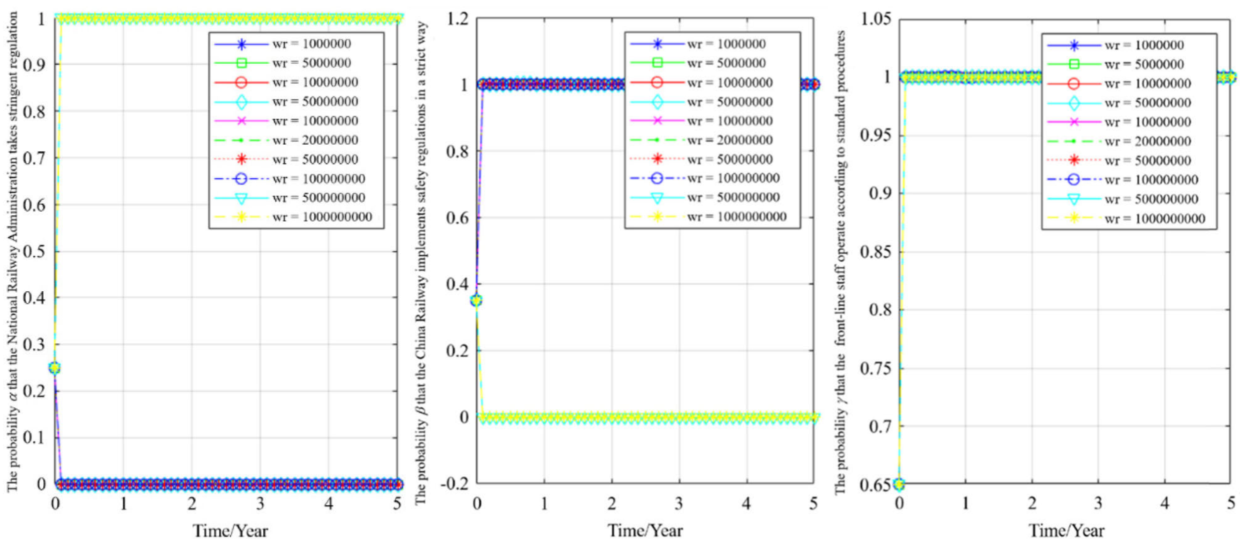


FIGURE 13. **The impact of the benefits from china railway's superficial supervision of front-line staff on evolution.**

standard procedures due to the income growth incentive. Therefore, in order to reach the Pareto optimal state (0, 1, 1), the value of y_s cannot be set too small. Improper setting of y_s will also cause game evolution oscillation. Fix other parameters of the system and set $y_s = 4986000$, i.e., $4985680 < y_s = 4986000 < 4988680$, so the system has no stable equilibrium point in this case. And the probability of National Railway Administration and staff choosing positive strategies will oscillate periodically. The specific evolution process is shown in Fig. 12.

E. THE INFLUENCE OF THE STAFF'S BENEFITS FROM SUPERFICIAL REGULATION ON THE EVOLUTION PATH

Only changing the value of w_r, the evolution result is shown in Fig. 13. It can be seen from Fig. 13 that there are two equilibrium outcomes: (0, 1, 1) and (1, 0, 1). Concrete analysis is as follows: ① No matter what the value of w_r is, γ always evolves to 1. That is, the staff adopt positive strategies. ② With the value increase of w_r ($w_r > 105150898$), β evolves from 1 to 0. I.e., because of the benefits increase from superficial regulations, it will encourage China Railway's speculative behavior and increase their willingness to implement safety regulations on the surface ③ With the value increase of w_r, α evolves from 0 (when $w_r < 105150898$, the eigenvalues λ_2 of Jacobi matrix at equilibrium point $E_4(0, 1, 1)$ is less than 0), to 1 (when $w_r > 105155965.94$, the eigenvalues λ_2 of Jacobi matrix at point $E_6(1, 0, 1)$ is less than 0). This is because when w_r is larger, if China Railway has chosen the negative strategy, then the National Railway Administration must choose strict supervision, so as to ensure

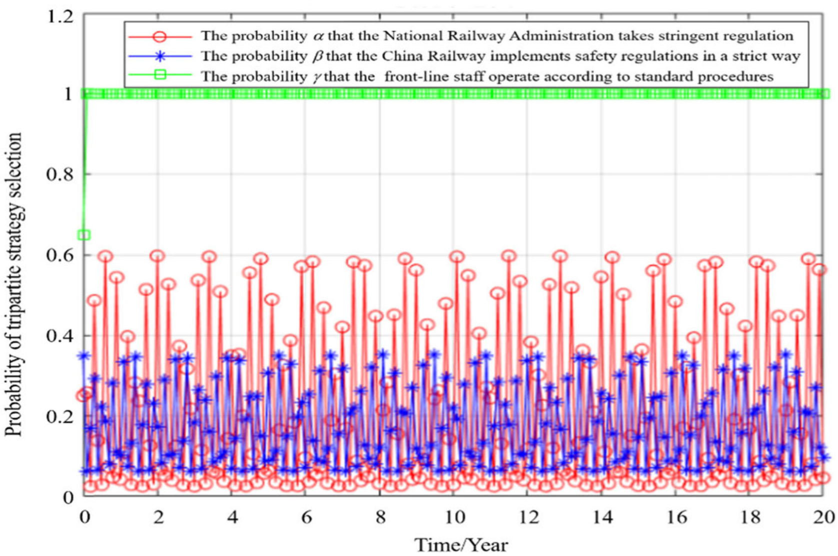


FIGURE 14. w_r = **105152000, evolutionary game fluctuates.**

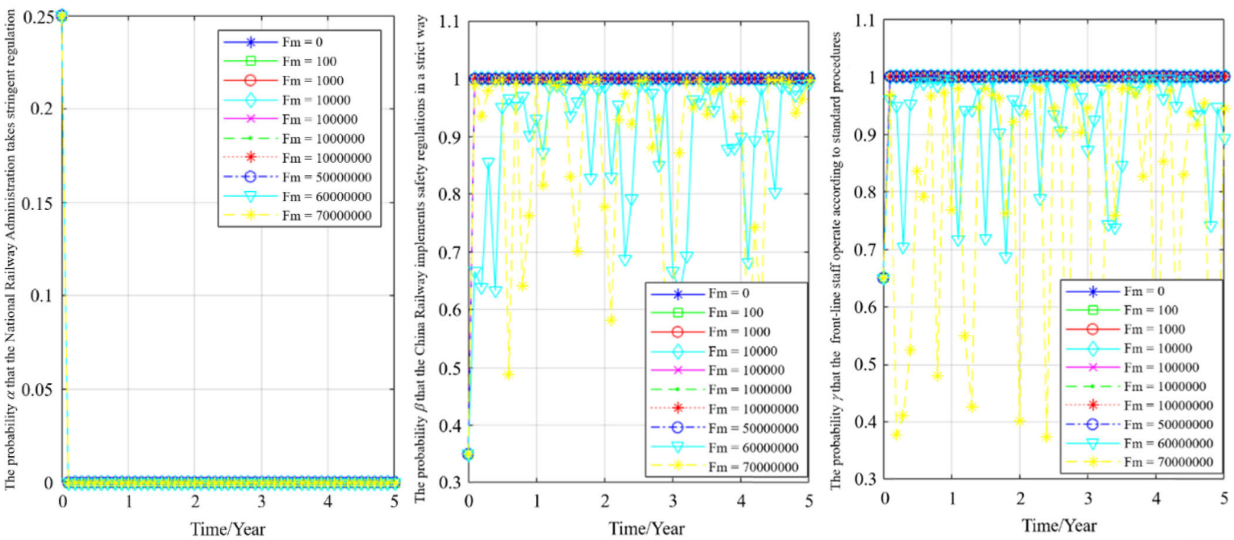


FIGURE 15. **The impact of collusion penalties imposed on staff by china railway safety on evolution.**

operation and production safety. Therefore, in order to reach the Pareto optimal state (0, 1, 1) in the two equilibrium points, the value of w_r cannot be set too large. Improper setting of w_r will also cause game evolution oscillation. Fix other parameters of the system and set $w_r = 105152000$, i.e., $105150898 < w_r = 105152000 < 105155965.94$, so the system has no stable equilibrium point in this case. And the probability of National Railway Administration and China Railway choosing positive strategies will oscillate periodically. The specific evolution process is shown in Fig. 14.

F. THE INFLUENCE OF THE STAFF'S COLLUSION PUNISHMENTS ON THE EVOLUTION PATH

Only changing the value of F_m, the evolution result is shown in Fig. 15. It can be seen from Fig. 15 that there is an equilibrium outcome (0, 1, 1) When F_m is small ($F_m < 55153398$). However, with the increase of F_m ($F_m > 55153398$), both β and γ evolve from 1 to the state of oscillation, that is, the system fluctuates up and down and repeatedly oscillates in the evolutionary game process, and there is no evolutionary stability strategy. This is because the collusion punishments come from that case: staff do not accept violation operation instructions, if the management layer of China Railway gives orders as it is clear that safe operating conditions are not available. And once the safety accident occurs, China Railway and staff need to assume the corresponding responsibility. So, when staff's collusion punishments from China Railway is too heavy ($F_m > 55153398$), it will make the willingness of China Railway and staff to choose a positive strategy wobble, and the probability of their choosing a positive strategy is highly volatile, as well as the outcome of the game is difficult to control. It can be seen from Table 2 that, for the current system, if other parameters are unchanged, when $F_m > 55153398$, at any equilibrium point from E_1 to E_8, it is impossible that λ_1, λ_2 and λ_3 cannot be less than 0 at the same time. So there is no evolutionary stable equilibrium state of the system. Therefore, in order to reach the Pareto optimal state (0, 1, 1) and improve the controllability of the game process, China Railway should not penalize staff too much for collusion.

VI. ADVICE GIVEN TO THE RAILWAY DEPARTMENT

The work of railway safety production and supervision is a systematic project with extensive scope, huge input and complicated situation, which have the characteristics of dynamic, multidimensional, relativity and diversity, and involves many related interest groups. Based on the model construction in this paper and the evolutionary game simulation results of the National Railway Administration of the People's Republic of China, the China State Railway Group Co., Ltd. and the front-line staff, the following suggestions are proposed:

(1) The current policy and management system are in a scientific and reasonable category. Under the guidance of the current policy, even if the initial values of α, β and γ are changed, the system can still reach the ideal state and realize Pareto optimality after tripartite evolution. Therefore, it is appropriate for the railway department to adopt the strategy of maintaining and continuing the current policy.

(2) There are many reasons leading to systematic deviation from Pareto optimality, including government policy making and market factors. The policy making factor refers to the setting of relevant parameters (cost, accident liability and fine) of the National Railway Administration safety regulatory agency. The model analysis finds that the railway safety regulatory system in China is in a positive and healthy state (which can evolve and stabilize at an ideal equilibrium point $E_4(0, 1, 1)$) under the current circumstances, and there is no need to take further strict supervision. It is of little significance for the railway safety supervision system to increase the political gains of the National Railway Administration, punish for its violation of the other two parties, crack down on the collusion reward of the staff of China Railway, and increase the punishment for the accident of the front-line staff who violate the production rules.

(3) Many parameters, including the safety regulatory supervision cost of the National Railway Administration, income of China Railway, the front-line staff's income gained by the production of compliance, the front-line staff's punishment from China Railway for collusion, and so on, their values change will cause the system to deviate from Pareto optimal state seriously.

To make the system achieve the Pareto optimal state, improve the controllability of game process, some parameters values cannot set too much is overweight such as the regulatory costs by China Railway, China Railway's benefits from the safety regulations on the surface, China Railway penalizes the staff for conspiracy, China Railway rewards the staff for compliance, and so on. And some parameters values cannot set too small. E.g. China Railway's benefits from the safety regulations in a strict way, benefits obtained from the compliance production of the staff.

VII. CONCLUSION

This paper constructs an evolutionary game model of National Railway Administration, China Railway and front-line staff in the process of railway safety production and supervision, and analyzes the evolutionary trend of behavior decisions of different interest groups. The results of evolution simulation are as follows:

(1) At present, the system is at an ideal state where the National Railway Administration does not choose strict supervision, China Railway implements safety regulations in a strict way, and front-line staff operate according to standard procedures. The current policy and management system are in a scientific and reasonable scope. Under the guidance of the current policy, even if the initial value of the strategy selection probability is changed, the system can finally evolve to an ideal state and achieve Pareto optimality.

(2) At present, China's railway safety supervision system is in a positive and healthy state. For the evolution of the railway safety supervision system, it is of little significance to implement one of the measures, such as to increase the political benefits of the National Railway Administration, the punishment of accountability and the penalty of violation against the other two parties, to crack down on the staff's collusion rewards given by China Railway, and to increase the staff's accountability punishment for the accidents of illegal production.

(3) There are many reasons why the system deviates from Pareto optimality. The change of parameters values will cause the system to deviate from the Pareto optimal state seriously, such as the cost and benefits of strict supervision of China Railways, the benefits of superficial supervision, the staff's collusion punishments, compliance rewards, and benefits obtained from the compliance production, and so on. In order to make the system reach the Pareto optimal state and improve the controllability of the game process, these parameters should be set appropriately.

This paper explains that railway safety supervision system impacts on the evolution of railway safety production guarantee method, and reveals the paths and ways of the railway safety supervision system responding to the changes of internal and external environment, as well as the game and transfer logic among different subjects. It will be the next research direction to further explore the influence of more relevant groups' behavioral decisions on guarantee safety effectiveness.

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