

A Study on the Evolutionary Game of In-Plant Transportation Modes from the Perspective of Benefit Synergy

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Abstract: To address the efficiency bottlenecks in the in-plant logistics of manufacturing enterprises and multi-stakeholder interest conflicts in the promotion of drop-and-pull transport, and to fill the research gaps where existing studies prioritize technical optimization while neglecting strategic interactions among stakeholders and lack rigorous quantification of efficiency losses, this paper constructs a three-party evolutionary game model consisting of truck drivers, loading and unloading teams, and enterprise managers, with the inbound logistics of auto parts as the research scenario. We introduce the operational blockage loss cost to replace the traditional subjective proportional coefficient, so as to quantify the economic losses caused by stakeholders' passive cooperation. The replicator dynamic equation is adopted to solve the system equilibrium points, the Jacobian matrix is applied to identify evolutionary stable strategies (ESS), and numerical simulation is performed to verify the influence mechanism of key parameters. The results demonstrate that the intensity of enterprise incentives and penalties, the distribution ratio of collaborative benefits, and post-specific blockage losses are core factors shaping the evolution trajectory of the system. The system can converge to the ideal state of tripartite collaboration when enterprises establish a sound incentive and constraint mechanism, control post-specific blockage losses, and optimize the benefit distribution scheme. The interest coordination mechanism proposed in this study provides theoretical support and practical reference for manufacturing enterprises to implement in-plant drop-and-pull transport and achieve logistics cost reduction and efficiency improvement.

Keywords: in-plant drop-and-hook transportation; tripartite evolutionary game; interest coordination; automotive parts logistics; evolutionary stable strategy

1. Introduction

With the organizational advantage of "separable tractors and trailers, and parallel operation of loading/unloading and transportation", drop-and-hook transportation can significantly improve vehicle turnover efficiency and reduce unit transportation costs, and is widely recognized as a green and efficient modern transportation mode. In countries with mature logistics industries such as Europe and the United States, 70% to 80% of road freight transportation has adopted the drop-and-hook transportation organization form ^[1]. China has gradually promoted the pilot work of drop-and-hook transportation since 2010 ^[2]. The application mode in trunk transportation scenarios has become increasingly mature, but its promotion in the field of in-plant production logistics is still in the exploratory stage. With the transformation of the automobile manufacturing industry towards lean and takt production, the traditional transportation mode of "one vehicle, one driver, one loading/unloading process" using wing-box trucks only achieves a comprehensive vehicle utilization rate of 30% to 40%, and the cross-waiting between drivers and loading/unloading teams is severe, which has become a key bottleneck restricting the response speed of the supply chain. Introducing drop-and-hook transportation into the in-plant short-haul scenario of parts to decouple transportation operations from loading/unloading operations can theoretically increase vehicle utilization to 70% to 80%. However, mode switching involves interest adjustment of multiple stakeholders, and practical problems such as frontline employee resistance and poor process coordination often arise during implementation, making it difficult to fully unleash the efficiency advantages of the mode.

Academia has carried out extensive research on the optimization and promotion of drop-and-hook transportation. Foreign scholars focus on the core issue of vehicle routing optimization. E. Zachariadis et al. ^[3] established the LDVRP model and proposed a local search algorithm to study the routing

problem of drop-and-hook transport vehicles. U. Derigs et al. [4] discussed the RVRP problem under specific circumstances and calculated the routes of trailers and tractors in drop-and-hook transportation using several flexible hybrid methods. M. Drexel [5] solved the vehicle routing problem of trailers and transshipment by describing and establishing the VRPMS model. O. Regnier-Coudert [6] solved the optimal scheduling scheme of drop-and-hook transportation through local search and hybrid heuristic algorithms, providing technical support for improving the efficiency of drop-and-hook transportation. Domestic scholars have further verified the energy conservation and emission reduction effects of trunk drop-and-hook transportation in combination with China's industrial scenarios. Li Hongqi et al. [7] constructed an LTDP integer programming model for intercity trunk transportation scenarios, and verified the energy conservation and emission reduction effects of drop-and-hook transportation through case calculations. Li Wei et al. [8] converted drop-and-hook transportation tasks into TSP problems and built a mathematical model to realize the optimal solution of vehicle travel routes. Liang Shibin et al. [9] constructed a combination optimization model of drop-and-hook transportation organization modes with the goal of minimizing total cost, providing quantitative decision-making basis for enterprise mode selection. Wang Zhengyu et al. [10] started from the perspective of market-oriented operation, analyzed the pricing logic of different modes using revenue management methods, and proposed a trailer rental pricing mechanism for rental drop-and-hook transportation, enriching the research system of drop-and-hook transportation operation management. Yang Yang et al. [11] compared the income differences between independent operation and alliance operation of enterprises based on the Cournot game model, derived the minimum profit distribution coefficient for drop-and-hook transportation enterprises to form alliances, and confirmed that business substitution degree, operation cost and market scale of enterprises operating independently are the core factors affecting alliance willingness, providing theoretical reference for the design of cross-stakeholder cooperation mechanisms.

However, existing studies still have two obvious shortcomings. First, most research scenarios focus on trunk transportation and inter-enterprise alliances, with little attention paid to the micro-production scenarios of in-plant drop-and-hook transportation in manufacturing enterprises, especially neglecting the interest conflicts and strategic interactions among enterprise managers, frontline transportation drivers, and loading/unloading teams during mode switching. Second, existing game models mostly use subjective proportional reduction coefficients when quantifying efficiency losses, making it difficult to accurately depict the operational blockage losses caused by negative behaviors at posts, and the fit between the models and actual operation scenarios needs to be improved. In fact, the implementation effect of in-plant drop-and-hook transportation is highly dependent on the coordinated cooperation of the three stakeholders: drivers' income faces a risk of decline due to reduced driving mileage, while loading/unloading teams face pressure of increased labor intensity. Resistance from any single stakeholder will cause process stagnation and turnover delay, thereby weakening enterprises' expected benefits from promoting the new mode. Therefore, analyzing the strategic evolution law of multiple stakeholders in in-plant drop-and-hook transportation from the perspective of benefit synergy has important theoretical value and practical significance.

Against this background, this paper takes the in-plant logistics of auto parts as the research background, constructs a three-party evolutionary game model including enterprise managers, transportation drivers, and loading/unloading teams, and introduces operational blockage loss cost to replace traditional proportional coefficients to quantify the economic losses caused by stakeholders' passive cooperation. The replicator dynamic equation is used to solve the system equilibrium points, the Jacobian matrix is combined to identify evolutionary stable strategies, and numerical simulation is conducted to analyze the influence mechanism of key parameters such as incentive intensity, penalty intensity, and benefit distribution ratio on the system evolution direction. Finally, a targeted benefit coordination mechanism is proposed to provide decision-making reference for manufacturing enterprises to smoothly promote the transformation of in-plant drop-and-hook transportation and achieve logistics cost reduction and efficiency improvement.

2. Model Construction

2.1. Model Symbols and Descriptions

Combined with the research scenario and basic assumptions, model parameters are uniformly defined, and all parameters are non-negative real numbers. The relevant symbols and their meanings of the model are shown in Table 1.

Table 1 Symbols and Their Descriptions

Symbol	Description
C_e	Initial input cost of the enterprise to promote drop-and-hook transportation
R_e	Total long-term efficiency benefit obtained by the enterprise after promoting drop-and-hook transportation
S_d	Special subsidy issued by the enterprise to drivers who cooperate with drop-and-hook transportation
S_l	Special subsidy issued by the enterprise to loading/unloading teams that actively participate in drop-and-hook transportation
F_d	Economic penalty imposed by the enterprise on drivers who resist drop-and-hook transportation
F_l	Economic penalty imposed by the enterprise on loading/unloading teams that passively respond to drop-and-hook transportation
R_{d0}	Basic benefit of drivers under the traditional transportation mode
R_{d1}	Basic benefit of drivers without subsidies under the drop-and-hook transportation mode
C_d	Extra cost incurred by drivers cooperating with drop-and-hook transportation
R_{l0}	Basic benefit of loading/unloading teams under the traditional transportation mode
R_{l1}	Basic benefit of loading/unloading teams without subsidies under the drop-and-hook transportation mode
C_l	Extra cost incurred by loading/unloading teams actively participating in drop-and-hook transportation
ΔR	Additional excess collaborative benefit generated by the system when the three parties fully cooperate
α	Proportion of collaborative benefits allocated to the enterprise
β	Proportion of collaborative benefits allocated to drivers
γ	Proportion of collaborative benefits allocated to loading/unloading teams
L_d	Operational blockage loss caused by drivers resisting drop-and-hook transportation
L_L	Operational blockage loss caused by passive operation of loading/unloading teams

2.2. Basic Assumptions of the Model

To ensure rigorous model logic and fit with real scenarios, combined with the operation characteristics of in-plant drop-and-hook transportation, the following basic assumptions are proposed:

(1) All three stakeholders are bounded rational, unable to make optimal decisions at one time, and will continuously learn, imitate, and adjust their strategies in the long-term game process to maximize their own benefits.

(2) The game is a dynamic evolutionary game. The proportion of strategy selection of each stakeholder changes continuously over time, and the system will eventually converge to a certain evolutionary stable state.

(3) The game information is incompletely symmetric. Each stakeholder only masters its own benefit function and cannot fully know the benefits and strategy choices of other stakeholders.

(4) Strategy set setting. For the behavioral strategies of game players, the strategy set of enterprise managers x indicates whether the enterprise actively promotes the in-plant drop-and-hook transportation strategy, where $x = \{x_1, x_2\}$, x_1 represents active promotion, and x_2 represents passive promotion. The strategy set of transportation drivers y indicates whether transportation drivers actively cooperate with the in-plant drop-and-hook transportation strategy, where $y = \{y_1, y_2\}$, y_1 represents active cooperation, and y_2 represents passive resistance. The strategy set of loading/unloading teams z indicates whether loading/unloading teams actively participate in the in-plant drop-and-hook transportation strategy, where $z = \{z_1, z_2\}$, z_1 represents active cooperation, and z_2 represents passive response. Specifically, the strategy set of enterprise managers is: promote drop-and-hook transportation, maintain traditional mode; the strategy set of transportation drivers is: cooperate with drop-and-hook transportation, resist drop-and-hook transportation; the strategy set of loading/unloading teams is: active participation, passive response.

(5) In-plant drop-and-hook transportation is highly dependent on tripartite collaboration. If drivers or loading/unloading teams show resistance or passive behaviors, it will cause process stagnation and turnover delay, resulting in operational blockage losses. Among them, drivers are the core post of transportation, and the blockage loss caused by their resistance behavior is greater than that caused by passive operation of loading/unloading teams.

2.3. Payoff Matrix

According to the problem description and model assumptions, the payoff matrix of the three-party game in in-plant transportation is obtained, as shown in Table 2.

Table 2 Payoff Matrix of the Three-Party Game Players

Player's strategy		Enterprise Implementation		Enterprise Maintenance	
		Loading/unloading active participation	Loading/unloading passive response	Loading/unloading active participation	Loading/unloading passive response
Transportation driver	Cooperation	$\begin{pmatrix} R_e - C_e - S_d - S_l + \alpha\Delta R \\ R_{d1} + S_d - C_d + \beta\Delta R \\ R_{l1} + S_l - C_l + \gamma\Delta R \end{pmatrix}$	$\begin{pmatrix} R_e - C_e - S_d - L_l + F_l \\ R_{d1} + S_d - C_d \\ R_{l1} - F_l \end{pmatrix}$	$\begin{pmatrix} 0 \\ R_{d0} - C_d \\ R_{l0} - C_l \end{pmatrix}$	$\begin{pmatrix} 0 \\ R_{d0} - C_d \\ R_{l0} \end{pmatrix}$
	Resistance	$\begin{pmatrix} R_e - C_e - S_l - L_d + F_d \\ R_{d0} - F_d \\ R_{l1} + S_l - C_l \end{pmatrix}$	$\begin{pmatrix} R_e - C_e - L_d - L_l + F_d + F_l \\ R_{d0} - F_d \\ R_{l0} - F_l \end{pmatrix}$	$\begin{pmatrix} 0 \\ R_{d0} \\ R_{l0} - C_l \end{pmatrix}$	$\begin{pmatrix} 0 \\ R_{d0} \\ R_{l0} \end{pmatrix}$

3. Evolutionary Game Analysis

3.1. Replicator Dynamic Equation

3.1.1. Expected benefit function and replicator dynamic equation of the enterprise

According to the analysis of the game payoff matrix, the expected benefit U_{e1} when the enterprise chooses the "promotion" strategy is:

$$U_{e1} = (R_e - C_e) + yz\alpha\Delta R + y(L_d - S_d - F_d) + z(L_l - S_l - F_l) + (F_d + F_l - L_d - L_l) \quad (1)$$

The expected benefit U_{e2} when the enterprise chooses the "maintenance" strategy is:

$$U_{e2} = 0 \quad (2)$$

Then the average benefit of the enterprise $\bar{U}_e$ is:

$$\bar{U}_e = xU_{e1} + (1-x)U_{e2} \quad (3)$$

According to the Malthusian dynamic equation, the replicator dynamic equation of the enterprise $F(x)$ is constructed as:

$$\begin{aligned} F(x) &= \frac{dx}{dt} \\ &= x(1-x)U_{e1} \\ &= x(1-x)[(R_e - C_e) + yz\alpha\Delta R + y(L_d - S_d - F_d) + z(L_l - S_l - F_l) + (F_d + F_l - L_d - L_l)] \end{aligned} \quad (4)$$

3.1.2. Expected benefit function and replicator dynamic equation of transportation drivers

According to the analysis of the game payoff matrix, the expected benefit U_{d1} when transportation drivers choose the "cooperation" strategy is:

$$U_{d1} = xz(R_{d1} + S_d - C_d + \beta\Delta R) + x(1-z)(R_{d1} + S_d - C_d) + (1-x)z(R_{d0} - C_d) + (1-x)(1-z)(R_{d0} - C_d) \quad (5)$$

The expected benefit U_{d2} when transportation drivers choose the "resistance" strategy is:

$$U_{d2} = xz(R_{d0} - F_d) + x(1-z)(R_{d0} - F_d) + (1-x)zR_{d0} + (1-x)(1-z)R_{d0} \quad (6)$$

Then the average benefit of transportation drivers $\bar{U}_d$ is:

$$\bar{U}_d = yU_{d1} + (1-y)U_{d2} \quad (7)$$

According to the Malthusian dynamic equation, the replicator dynamic equation of transportation drivers $F(y)$ is constructed as:

$$\begin{aligned} F(y) &= \frac{dy}{dt} \\ &= y(1-y)(U_{d1} - U_{d2}) \\ &= y(1-y)[x(R_{d1} - R_{d0} + S_d + F_d + \beta\Delta R \cdot z) - C_d] \end{aligned} \quad (8)$$

3.1.3. Expected benefit function and replicator dynamic equation of loading/unloading teams

According to the analysis of the game payoff matrix, the expected benefit U_{11} when loading/unloading teams choose the "active participation" strategy is:

$$U_{11} = xy(R_{11} + S_l - C_l + \gamma\Delta R) + x(1-y)(R_{11} + S_l - C_l) + (1-x)y(R_{10} - C_l) + (1-x)(1-y)(R_{10} - C_l) \quad (9)$$

The expected benefit U_{12} when loading/unloading teams choose the "passive response" strategy is:

$$U_{12} = xy(R_{11} - F_l) + x(1-y)(R_{10} - F_l) + (1-x)yR_{10} + (1-x)(1-y)R_{10} \quad (10)$$

Then the average benefit of loading/unloading teams $\overline{U}_l$ is:

$$\overline{U}_l = zU_{11} + (1-z)U_{12} \quad (11)$$

According to the Malthusian dynamic equation, the replicator dynamic equation of loading/unloading teams $F(z)$ is constructed as:

$$\begin{aligned} F(z) &= \frac{dz}{dt} \\ &= z(1-z)(U_{11} - U_{12}) \\ &= z(1-z)[x((1-y)(R_{11} - R_{10}) + S_l + F_l + \gamma\Delta R \cdot y) - C_l] \end{aligned} \quad (12)$$

3.2. Stability Analysis

According to the evolutionary game equilibrium solution method of RITZBERGER K. [12], let the dynamic replication equations of the various agents in the change of in-plant transportation modes be equal to 0, that is, set Equations (4), (8), and (12) simultaneously to 0, to obtain the equilibrium points of the in-plant transportation mode changes.

$$\begin{cases} F(x) = 0 \\ F(y) = 0 \\ F(z) = 0 \end{cases} \quad (13)$$

By solving equation (13), we obtain and only need to discuss the stability of the eight special equilibrium points: (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). According to Lyapunov's stability theory, by taking the partial derivatives of the replicator dynamic equations of the three game participants, namely equations (4), (8), and (12), the Jacobian matrix is obtained. The eigenvalues of the matrix at each equilibrium point are then analyzed to determine the asymptotic stability of the rail-road combined transport system. The Jacobian matrix J is:

$$\begin{bmatrix} (1-2x)U_{e1} & x(1-x)(z\alpha\Delta R + L_d - S_d - F_d) & x(1-x)(y\alpha\Delta R + L_l - S_l - F_l) \\ y(1-y)(R_{d1} - R_{d0} + S_d + F_d + z\beta\Delta R) & (1-2y)\Delta U_d & xy(1-y)\beta\Delta R \\ z(1-z)[(1-y)(R_{11} - R_{10}) + S_l + F_l + y\gamma\Delta R] & xz(1-z)(\gamma\Delta R + R_{10} - R_{11}) & (1-2z)\Delta U_l \end{bmatrix} \quad (14)$$

Substitute the eight special equilibrium points into the Jacobian matrix, and obtain the corresponding eigenvalues according to the matrix eigenvalue method, as shown in Table 3.

Table 3 Eigenvalues of Equilibrium Points in the Game System

Equilibrium Point	Eigenvalue		
	λ_1	λ_2	λ_3
(0,0,0)	$R_e - C_e + F_d + F_l - L_d - L_l$	$-C_d$	$-C_l$
(0,0,1)	$R_e - S_l - L_d + F_d - C_e$	$-C_d$	C_l

(0,1,0)	$R_e - S_d - L_l + F_l - C_e$	C_d	$-C_l$
(0,1,1)	$\alpha\Delta R + R_e - S_d - S_l - C_e$	C_d	C_l
(1,0,0)	$L_d + L_l + C_e - F_d - F_l - R_e$	$R_{d1} - R_{d0} + S_d + F_d - C_d$	$R_{l1} - R_{l0} + S_l + F_l - C_l$
(1,0,1)	$C_e + S_l + L_d - R_e - F_d$	$R_{d1} - R_{d0} + S_d + F_d + \beta\Delta R - C_d$	$C_l + R_{l0} - R_{l1} - S_l - F_l$
(1,1,0)	$C_e + S_d + L_l - R_e - F_l$	$C_d + R_{d0} - R_{d1} - S_d - F_d$	$S_l + F_l + \gamma\Delta R - C_l$
(1,1,1)	$C_e + S_d + S_l - R_e - \alpha\Delta R$	$C_d + R_{d0} - R_{d1} - S_d - F_d - \beta\Delta R$	$C_l - S_l - F_l - \gamma\Delta R$

4. Numerical Simulation

4.1. Analysis of Ideal Evolution Path

From the above analysis, it can be seen that equilibrium points $e_2(0,0,1)$, $e_3(0,1,0)$, and $e_4(0,1,1)$ are unstable points, while the remaining five equilibrium points, under the premise of satisfying their respective stability conditions, are all asymptotically stable points. The equilibrium point at which the entire system is in an ideal stable state is $e_8(1,1,1)$, indicating that the enterprise implements a new transportation model, transportation drivers cooperate, and the loading and unloading team actively participates. A numerical simulation analysis of $e_8(1,1,1)$ was conducted in the study. Based on the expression of the eigenvalues of $e_8(1,1,1)$ and through simulation optimization, a relatively ideal set of parameters was ultimately selected, with parameter values set as follows: $C_e=12$, $R_e=35$, $S_d=4$, $S_l=3$, $F_d=5$, $F_l=4$, $R_{d0}=14$, $R_{d1}=18$, $C_d=2$, $R_{l0}=15$, $R_{l1}=16$, $C_l=1.5$, $\Delta R=12$, $\alpha=0.5$, $\beta=0.3$, $\gamma=0.2$, $L_d=8$, $L_l=4$. The initial strategy selection probabilities x , y , and z of the enterprise, transportation drivers, and loading/unloading team were all set to 0.5. The simulation evolution is shown in Figure 1.

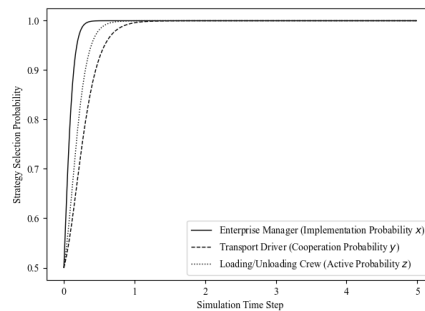


Figure 1 Evolutionary path of the in-plant drop-and-hook tripartite game system at the equilibrium point (1,1,1)

4.2. The Impact of Initial Willingness of Each Entity on Evolutionary Outcomes

With the initial strategy probabilities of enterprises, drivers and loading/unloading teams uniformly set at $x = y = z = 0.5$, the system's benchmark evolutionary trajectory is simulated using standard incentive, penalty and revenue distribution parameters. As shown in Figure 1, the three curves rise monotonically without oscillation or regression, and finally converge synchronously to 1, stabilizing at the ideal equilibrium point (1,1,1). Under benchmark parameters, enterprise subsidies compensate frontline teams for extra labor costs; synergy benefits from tripartite collaboration are distributed by job contribution, offsetting enterprises' initial investment in trailers and site modification. Meanwhile, operational delays from negative behaviors plus economic penalties greatly reduce the net benefits of non-cooperative strategies. Boundedly rational agents gradually imitate high-yield collaborative behaviors, spontaneously forming a three-party cooperative steady state. In conclusion, with balanced incentive, penalty and revenue distribution mechanisms, no mandatory administrative control is needed; the three parties will voluntarily adopt the in-factory drop-and-hook model in the long-term game.

4.2.1. The impact of changes in y and z values on the evolution of corporate strategy

The initial implementation probability of enterprises is fixed at $x = 0.5$, and four groups of initial combinations of frontline subjects are set: ($y = 0.1$, $z = 0.1$) both resistant, ($y = 0.1$, $z = 0.9$) drivers resistant but loaders proactive, ($y = 0.9$, $z = 0.1$) drivers cooperative but loaders passive, and ($y = 0.9$, $z = 0.9$) all cooperative.

= 0.9) both proactive. The evolutionary results show that under all four initial combinations, the enterprise implementation probability eventually converges to 1; the initial willingness combinations only affect the convergence speed, not the final evolutionary trend. The order of convergence speed is: $(0.9, 0.9) > (0.1, 0.9) > (0.9, 0.1) > (0.1, 0.1)$. As shown in Figure 2, in scenarios where both drivers and loaders have high willingness to cooperate, the enterprise strategy converges the fastest; when both parties are initially resistant, the increase in the enterprise's willingness to implement is the slowest.

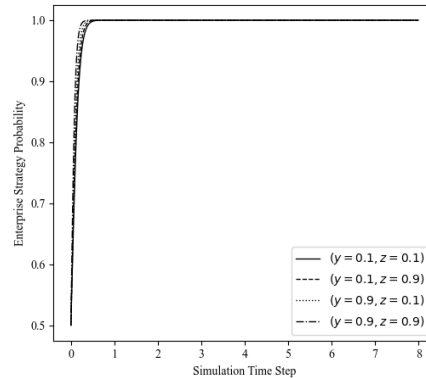


Figure 2 The Impact of y and z Value Changes on the Evolution of Corporate Strategy

4.2.2. The Impact of Changes in x and z Values on Driver Strategy Evolution

With fixed drivers' initial cooperation probability set at $y = 0.5$, four initial combinations of enterprise implementation willingness (x) and loading/unloading activeness (z) are constructed: $(0.1, 0.1)$, $(0.1, 0.9)$, $(0.9, 0.1)$, $(0.9, 0.9)$. As shown in Figure 3, the enterprise's initial implementation willingness is the key determinant of drivers' evolution trend. When $x = 0.9$, drivers' cooperation probability eventually converges to 1 regardless of loading/unloading's initial state; when $x = 0.1$, drivers' cooperation probability stays low long-term, no matter how active loading/unloading teams are. Meanwhile, under enterprise implementation, passive loading/unloading significantly slows the convergence speed of drivers' strategies. Driver-specific subsidies and collaborative excess profit distribution are only available when the enterprise actively adopts the drop-and-hook model. Under the traditional mode, there is no extra compensation and drivers' piece-rate income declines, eliminating their cooperation incentive. Even with the new mode, process bottleneck losses from passive loading/unloading are shared across the chain, reducing drivers' overall income and weakening their cooperation willingness. Mobilizing drivers alone cannot resolve resistance; enterprises must actively roll out supporting incentives while regulating loading/unloading teams' operational behavior, to prevent individual participants from losing collaborative benefits.

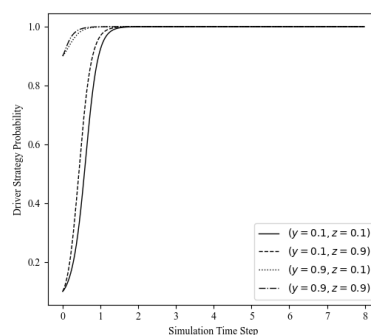


Figure 3 The Impact of x and z Value Changes on the Evolution of Driver Strategies

4.2.3. The Impact of Changes in x and y Values on the Evolution of Loading and Unloading Team Strategies

The initial probability of fixed loading and unloading being proactive is $z = 0.5$, with four sets of initial combinations established: $(0.9, 0.9)$ enterprise promotion and driver cooperation, $(0.9, 0.1)$ enterprise promotion and driver resistance, $(0.1, 0.9)$ enterprise maintenance and driver cooperation, $(0.1, 0.1)$ both negative. As shown in Figure 4, the enterprise's willingness to promote determines the evolutionary direction of the loading and unloading teams: when $x = 0.9$, the loading and unloading ultimately converge to active participation; when $x = 0.1$, the loading and unloading remain negative in the long term. Under the enterprise promotion scenario, driver resistance significantly slows the

convergence of the loading and unloading teams. Mechanism analysis shows that subsidies and collaborative gains for the loading and unloading teams rely on the enterprise's promotion model; as drivers are core positions in transportation, resistance generates higher inertia losses L_d , preventing the realization of excess collaborative benefits. The additional costs of high-intensity continuous work by the loading and unloading teams cannot be compensated, making short-term gains from passive shirking higher. The root cause of resistance in loading and unloading teams is not simply an increase in labor load, but process losses and profit shrinkage caused by driver resistance; enterprise transformation must first address the pain point of declining driver income, and coordination between the two main entities is required to release the willingness of loading and unloading teams to cooperate.

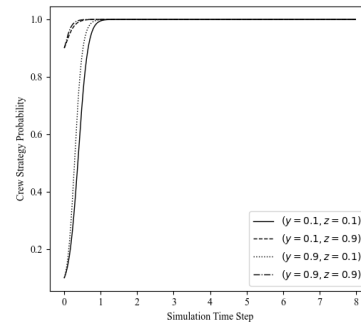


Figure 4 Impact of changes in x and y values on the evolution of loading and unloading team strategies

4.3. The Impact of Corporate Behavior on Evolutionary Outcomes

4.3.1. Impact of Changes in Driver Subsidies on the Evolution of Driver Cooperation Probability

Keeping other parameters unchanged, three levels of subsidies are set: $S_d = 2$, $S_d = 4$, and $S_d = 6$. As shown in Figure 5, under all three types of subsidies, the driver cooperation probability converges to 1; the subsidy level is positively correlated with the convergence speed, with the $S_d = 6$ high subsidy curve approaching the steady state fastest, while in the $S_d = 2$ low subsidy scenario, the evolution cycle is significantly prolonged, making full cooperation difficult to achieve in the long term. Mechanism analysis shows that under the drop-and-hook mode, the driver's mileage decreases and basic piece-rate income drops. Special subsidies directly offset the income gap, compensating for the cost of adapting to the new model; the higher the subsidy, the greater the difference in payoff between the 'cooperate' and 'resist' strategies, leading boundedly rational drivers to quickly imitate high-payoff cooperative behavior. However, continuously increasing subsidies raises the initial investment cost for enterprises, implying an economically optimal threshold. The subsidy standard should match the decline in driver income and should not be set too low; at the same time, it should be balanced with the long-term operational efficiency gains of the enterprise to optimize subsidy investment costs.

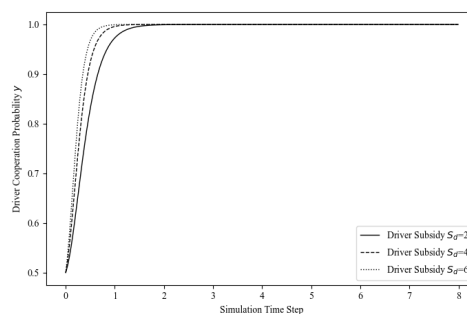


Figure 5 Impact of S_d Variation on the Evolution of Driver Cooperation Probability

4.3.2. Impact of Changes in Loading and Unloading Subsidies on the Evolution of Team Cooperation Probability

With other parameters held constant, three levels of loading and unloading subsidies are set: $S_l = 1$ (low), $S_l = 3$ (baseline), and $S_l = 5$ (high). As shown in Figure 6, the higher the subsidy, the faster the probability of teams actively working converges; the low subsidy $S_l = 1$ results in a slowly increasing curve, making it difficult to achieve full participation over the long term. Drop-and-hook transportation eliminates idle periods in loading and unloading, but continuous work by teams incurs additional labor costs, and special subsidies offset the incremental labor costs. When subsidies are insufficient, the net

benefit of active work is lower than the effort-saving benefit of passive shirking, leading teams to respond passively. The management implication is to implement differentiated subsidies based on the increase in labor load for loading and unloading positions; the higher the work intensity, the higher the corresponding subsidy standard.

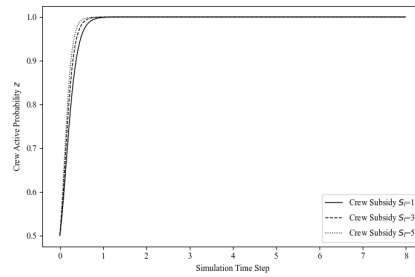


Figure 6 Effect of S Variation on the Evolution of Coordination Probability of Loading and Unloading Teams

4.3.3. The Impact of Changes in Driver Penalties on the Evolution of Drivers' Cooperation Probability

With other parameters unchanged, three levels of penalty intensity are set: $F_d=3$ (light penalty), $F_d=5$, $F_d=7$. As shown in Figure 7, the greater the penalty, the faster drivers converge to the cooperation strategy; under the light penalty $F_d=3$, the economic loss of resisting behavior is small, leading to a prolonged observation period by drivers and a slow increase in willingness to cooperate. Economic penalties increase the opportunity cost of drivers' negative resistance, so resisting behavior simultaneously bears the dual loss from fines and delayed penalties; if the penalty intensity is insufficient, the short-term gains from resistance still have an advantage, making it difficult for the system to evolve toward a cooperative equilibrium.

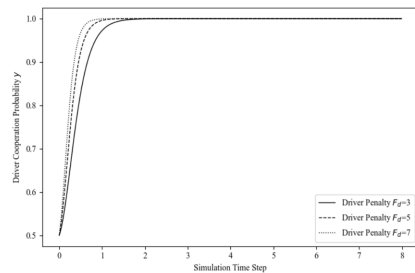


Figure 7 Impact of F_d Variation on the Evolution of Driver Cooperation Probability

4.3.4. Impact of Changes in Loading and Unloading Penalties on the Evolution of Driver Cooperation Probability

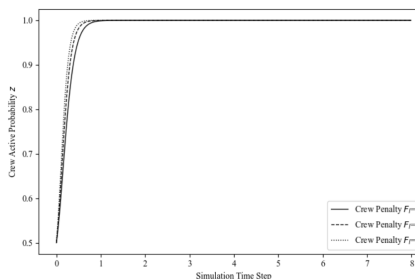


Figure 8 Impact of F Variation on the Evolution of Driver Cooperation Probability

With other parameters unchanged, three penalty intensity levels are set: $F_l=2$, $F_l=4$, and $F_l=6$. As shown in Figure 8, the strength of loading and unloading penalties is positively correlated with the speed of team engagement; under the low penalty scenario of $F_l=2$, the cost of passive shirking is very low, and team enthusiasm remains consistently low; under high penalty $F_l=6$, the constraint effect is significant, leading to rapid convergence to full engagement. Passive loading and unloading operations cause terminal turnover delays, and enterprise economic penalties further amplify the losses from passive behaviors; light penalties cannot offset the short-term benefits of 'laziness and effort savings,' resulting in persistently low team engagement; with high-intensity penalties, the net benefit advantage

of active operations becomes apparent.

5. Conclusion and Outlook

The research shows that: First, the three-party game system of in-plant drop-and-hook transportation has multiple evolutionary stable equilibria. When enterprises set up a reasonable incentive and constraint mechanism, control post blockage losses, and optimize the collaborative benefit distribution scheme, the system can converge to the ideal collaborative state of "enterprise promotion, driver cooperation, and active participation of loading/unloading teams", which verifies the positive driving effect of the benefit coordination mechanism on mode transformation. Second, the active promotion of the enterprise is the core premise for frontline stakeholders to shift to collaborative strategies. The initial cooperation willingness of drivers and loading/unloading teams only affects the convergence rate of the system and does not change the final evolution direction; among them, as the core post of transportation, drivers' strategy choices will be transmitted to loading/unloading teams through the operational blockage effect, thereby affecting the overall convergence efficiency of the system. Third, incentives, penalties and benefit sharing have complementary effects: special subsidies can offset the extra labor costs and income gaps of frontline posts, and economic penalties can increase the opportunity cost of passive behaviors. The combination of the two can accelerate the formation of collaborative steady state on the premise of controlling the enterprise's investment cost; and the collaborative benefit distribution mechanism based on post contributions is the core foundation to ensure the long-term stable collaboration of the three parties.

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