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Evolutionary Game Analysis of Hazardous Materials Transport Regulation under a Dynamic Assessment Mechanism

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ABSTRACT

To improve the effectiveness of local governments in supervising hazardous materials transportation enterprises and to ensure transportation safety, this study applies evolutionary game theory to investigate the strategic interactions between local governments and hazardous materials transport enterprises. Based on the assumptions of bounded rationality and dynamic strategy adjustment, a payoff matrix is established, and an evolutionary game model is constructed to describe the decision-making behaviors of both parties. The stability and evolutionary trajectories of the system are analyzed through the Jacobian matrix, and MATLAB simulation tools are employed to verify the theoretical results and visualize the dynamic evolution process. Furthermore, a dynamic assessment mechanism from higher-level governments is introduced to develop a new dynamic payoff matrix, aiming to investigate the impact of a transport safety and quality-oriented dynamic assessment mechanism on the effectiveness of safety regulation. The results indicate that the implementation of the dynamic assessment mechanism can significantly enhance the effectiveness of safety regulation. Specifically, hazardous materials transportation enterprises are more likely to maintain a high willingness to comply with transportation regulations, while local governments tend to adopt stricter supervision strategies. As a result, the evolutionary strategies of both parties gradually converge to a stable equilibrium, thereby improving overall transportation safety. However, the application of such mechanisms should also fully consider the influence of environmental conditions and other uncontrollable factors on

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transportation safety to ensure fairness and effectiveness in performance evaluation.

Keywords: Hazardous Materials Transport; Dynamic Assessment Mechanism; Regulation; Evolutionary Game

1. Introduction

In recent years, the rapid development of the global chemical industry and international trade has led to a substantial increase in the transportation of hazardous materials. Hazardous materials, including flammable, explosive, toxic, corrosive and radioactive substances, play an essential role in a wide range of industries, such as petrochemicals, pharmaceuticals, energy production and advanced manufacturing. As global supply chains become increasingly interconnected, the safe transportation of hazardous materials has become a critical prerequisite for maintaining industrial production and economic stability. Consequently, governments and international organizations have continuously strengthened the regulatory framework governing hazardous materials transportation. For example, the United Nations Economic Commission for Europe (UNECE) regularly updates the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) regulations for the international carriage of dangerous goods by road, while the Organisation for Economic Co-operation and Development (OECD) issued the third edition of its *Guiding Principles for Chemical Accident Prevention, Preparedness and Response* in 2023, emphasizing integrated risk management and coordinated supervision throughout the transportation chain. These initiatives reflect the growing international consensus that effective regulatory mechanisms are essential for ensuring transportation safety and sustainable industrial development.

Hazardous materials transportation constitutes a key component of modern supply chains because raw materials and chemical products must frequently be transported between manufacturers, storage facilities, ports, and end users. Unlike ordinary freight transportation, however, hazardous materials transportation is characterized by significant uncertainty and high levels of risk. Although transportation accidents occur relatively infrequently, they often produce catastrophic consequences involving casualties, environmental pollution, infrastructure damage, and severe economic losses. Furthermore, hazardous materi-

als accidents frequently exhibit cascading effects. A single transportation accident may trigger explosions, fires, toxic gas dispersion, traffic disruption, emergency evacuation, and long-term environmental contamination, thereby amplifying both direct and indirect losses. Recent reviews of hazardous materials transportation risk assessment have emphasized that accident prevention cannot rely solely on self-management by transportation enterprises. It also needs effective government supervision, standard operating procedures, real-time monitoring technology, and coordinated emergency response systems^[1]. International organizations have also pointed out that hazardous materials transportation involves many stakeholders, including governments, carriers, logistics operators, emergency responders, and the public^[2]. Therefore, effective regulatory coordination is important for reducing overall risks and improving the safety and resilience of hazardous materials transportation.

Despite continuous improvements in safety management, hazardous materials transportation accidents continue to occur worldwide. In 2023, the derailment of a freight train transporting hazardous chemicals in East Palestine, Ohio, United States, resulted in the release and controlled burning of vinyl chloride, causing widespread environmental concerns and large-scale evacuations^[3]. Earlier, the explosion at the Port of Beirut in Lebanon in 2020 demonstrated how hazardous chemicals can generate catastrophic social and economic consequences when safety management fails^[4]. These representative accidents indicate that failures in transportation management not only threaten human life and property but may also generate long-term environmental and social impacts. Therefore, establishing effective regulatory mechanisms capable of motivating both governments and transportation enterprises to continuously improve safety performance has become an important research issue in both academia and practice.

In response to the growing safety risks associated with hazardous materials transportation, governments around the world have adopted a variety of regulatory approaches. Traditional regulatory measures mainly include administrative inspections, safety audits, electronic monitoring technolo-

gies, and public participation mechanisms. Administrative inspections and routine safety audits are widely used to ensure that transportation enterprises comply with relevant laws, regulations, and operational standards. Meanwhile, the rapid development of digital technologies has promoted the application of electronic monitoring systems, such as global positioning system (GPS) tracking, intelligent sensors, and real-time data transmission, which improve the transparency of transportation processes and enhance the capability of regulators to detect potential safety risks. In addition, public participation through accident reporting, information disclosure, and social supervision has gradually become an important complement to formal government regulation. Despite these efforts, existing regulatory approaches still face several limitations. First, maintaining continuous inspections and safety audits requires substantial financial and human resources, resulting in high regulatory costs, particularly for local governments with limited regulatory capacity. Second, information asymmetry between regulators and transportation enterprises makes it difficult for governments to accurately assess the actual safety conditions of transportation activities. Enterprises often possess more complete operational information and may conceal unsafe behaviors to reduce compliance costs. Third, local governments may lack sufficient incentives to maintain long-term strict supervision due to budget constraints, competing administrative priorities, or imperfect performance evaluation systems. Finally, some transportation enterprises may adopt opportunistic behaviors by underestimating accident risks or assuming a low probability of regulatory detection thereby reducing their willingness to fully comply with safety regulations. Consequently, improving regulatory effectiveness requires not only stronger enforcement measures but also more effective incentive mechanisms capable of encouraging both governments and transportation enterprises to maintain long-term commitments to transportation safety.

A large number of scholars have conducted extensive research in the field of hazardous materials transportation regulation. For instance, Abkowitz et al.^[5] first constructed a scientific hazardous materials transportation safety evaluation system, providing a foundation for subsequent safety assessment studies. Erkut et al.^[6] applied operations research models to analyze the core issue of risk in hazardous

materials logistics and investigated routing and scheduling problems in hazardous materials transportation. Kara and Verter^[7] developed a bilevel programming model to study how decisions made by regulators and carriers affect the selection of hazardous materials transportation routes. Based on existing models, Berman et al.^[8] innovatively introduced a greedy algorithm to optimize the layout of emergency response networks for hazardous materials transportation, aiming to improve emergency response efficiency and reduce the adverse consequences of hazardous materials leakage incidents. El-Basyouny and Sayed^[9] constructed a dynamic routing support system for hazardous materials transportation by integrating GIS and climatic conditions, and examined route optimization and risk control from multiple dimensions such as safety, efficiency, and cost. Ke et al.^[10] proposed a scenario-based network design model integrating proactive and reactive risk mitigation mechanisms and studied the impact of regulatory policies on risk control and routing decisions in hazardous materials transportation networks. More recently, Guo and Luo^[11] systematically reviewed more than 30 years of hazardous materials transportation risk assessment research and pointed out that road transportation has been extensively studied, whereas railway and multimodal transportation still require further investigation. They also highlighted that incorporating human behavior and decision-making into transportation risk assessment remains an important future research direction. Mohri et al.^[12] comprehensively reviewed hazardous materials transportation models from the perspective of operations research and summarized the latest advances in routing, routing-scheduling, and network design problems, while identifying several promising research directions such as integrating multiple optimization objectives and considering uncertainty in transportation networks. Furthermore, Hu et al.^[13] proposed a dynamic routing algorithm for hazardous materials transportation based on real-time traffic information, demonstrating that dynamic route adjustment can effectively reduce transportation risks and improve operational efficiency under changing traffic conditions.

In recent years, the application of evolutionary game theory in the field of hazardous materials transportation has attracted increasing research attention. Evolutionary game theory is based on the assumption of bounded rationality and provides a theoretical framework that integrates game theory

with evolutionary biology to study the evolution of individual strategies under natural selection and population dynamics. It was first introduced by Smith and Price^[14] in 1973 in their study of symmetric population games. Since then, it has been widely applied to analyze various economic phenomena. In 2022, Wang et al.^[15] developed an evolutionary game model between governments and transportation enterprises in the context of hazardous materials transportation regulation. They analyzed the evolutionary path of illegal transportation behavior under conditions of public supervision and demonstrated that public participation in supervision can significantly enhance governmental regulatory effectiveness and increase enterprise compliance probability. Xu et al.^[16] further constructed a dynamic evolutionary game model between governments and chemical enterprises from the perspective of chemical safety production regulation. Their findings indicate that strengthening punishment mechanisms and regulatory intensity can effectively drive enterprises toward safe production strategies; however, the system still exhibits notable dynamic instability. Shen et al.^[17] developed a three-party evolutionary game model involving government, training institutions, and the public in the regulation of hazardous materials transportation training and investigated the evolutionary patterns of strategies under multi-agent interaction. The results show that the equilibrium state of the system is highly dependent on key parameters such as regulatory costs, penalty intensity, and information transparency. Guo et al.^[18] constructed an evolutionary game model between government agencies and enterprises to investigate collaborative strategies for coping with Natech risks. Their results showed that government incentive mechanisms and enterprise investment decisions jointly determine the evolutionary stability of the system, highlighting the importance of effective regulatory incentives in promoting enterprise participation in risk management. Wu et al.^[19] incorporated reinforcement learning into a game-theoretic framework to analyze hazardous chemicals transport route selection and found that appropriate governmental intervention can guide enterprises toward safer routing strategies. Furthermore, a recent review by Ahmad et al.^[20] summarized the application of evolutionary game theory in transportation systems and highlighted its advantages in modeling dynamic strate-

gic interactions among multiple stakeholders under bounded rationality.

However, existing studies have two main limitations. First, most studies primarily focus on the ideal boundary equilibrium, where governments consistently implement strict supervision and transportation enterprises always comply with safety regulations, while insufficient attention has been paid to the dynamic evolutionary process of interior equilibrium points. In reality, the strategies of both governments and transportation enterprises are constantly adjusted through interactions and learning, and the evolutionary trajectories may not directly converge to the ideal boundary equilibrium. Therefore, investigating the stability and evolution mechanisms of interior equilibrium points is essential for understanding the dynamic changes of regulatory behaviors. Second, existing studies are mainly based on relatively static regulatory environments, assuming that regulatory policies and incentive mechanisms remain unchanged over time. Nevertheless, in practice, regulatory effectiveness often depends on continuous assessment and feedback mechanisms that dynamically adjust incentives and constraints for different participants. The lack of consideration of dynamic assessment mechanisms limits the ability of existing models to reflect the long-term evolution of hazardous materials transportation safety regulation.

To address these research gaps, this study adopts an evolutionary game analysis method^[21] to construct an evolutionary game model between local governments and hazardous materials transportation enterprises and investigates the strategic evolution of both parties in the regulatory process. To address the strategic instability between the two participants, a dynamic assessment mechanism oriented toward transportation safety quality is further introduced to examine how higher-level governments influence the evolutionary stable strategies of local governments and transportation enterprises through such an assessment system. Compared with previous evolutionary game studies, the main innovations of this study are summarized in **Table 1**. This study provides theoretical insights and practical implications for optimizing regulatory strategies and improving the efficiency of hazardous materials transportation safety regulation.

Table 1. Comparison of this study with previous evolutionary game studies on hazardous materials transportation regulation.

Comparison Aspects	Previous Evolutionary Game Studies	This Study's Contributions and Novelty
Analysis of equilibrium states	Existing studies mainly focus on ideal boundary equilibrium states, assuming that local governments always adopt strict supervision strategies and hazardous materials transportation enterprises always choose legal transportation behaviors. The evolutionary process of interior equilibrium points has received limited attention.	This study further investigates the dynamic evolution process of interior equilibrium points, analyses the stability and evolutionary trajectories of different strategic states, and provides a more comprehensive understanding of the interaction mechanisms between governments and transportation enterprises.
Regulatory environment setting	Most existing studies are developed under relatively static regulatory environments, where regulatory policies, incentives, and constraints are assumed to remain unchanged during the evolutionary process.	This study introduces a dynamic assessment mechanism oriented toward transportation safety quality, enabling regulatory incentives and constraints to be dynamically adjusted according to safety performance changes.
Role of government participation	Previous studies mainly consider the interaction between regulatory authorities and transportation enterprises but pay less attention to how higher-level governments can influence local regulatory behaviors through evaluation and feedback mechanisms.	This study incorporates higher-level government participation into the evolutionary game framework and examines how dynamic assessment mechanisms influence the strategic evolution of local governments and transportation enterprises.

2. Model Assumptions

2.1. Game Participants

Hazardous materials transportation regulation involves multiple stakeholders, including government authorities, transportation enterprises, regulatory agencies, and the public. However, local governments and hazardous materials transportation enterprises are regarded as the two core participants in this evolutionary game model because they directly determine the effectiveness of safety regulation through their strategic interactions. On the one hand, transportation enterprises are the direct executors of hazardous materials transportation activities, and their decisions regarding compliance or violation behaviors have a direct impact on transportation safety risks. On the other hand, local governments are the primary regulators responsible for implementing safety supervision, allocating regulatory resources, and imposing penalties on violations within their jurisdictions. Although other stakeholders may influence the regulatory environment, their impacts are relatively indirect compared with the strategic interactions between governments and enterprises. Therefore, this study focuses on these two participants to capture the strategic interaction between regulatory enforcement and enterprise compliance decisions.

Based on this argument, the evolutionary game model involves two participants: local governments and hazardous materials transportation enterprises. Both participants continuously adjust their strategies through repeated interactions until the system reaches a relatively stable evolutionary state.

Hazardous materials transportation enterprises have two alternative strategies: legal transportation and illegal trans-

portation. Legal transportation means that enterprises comply with all relevant laws, regulations, and safety standards during the transportation process. This includes employing qualified personnel, maintaining transportation vehicles and equipment, following prescribed transportation routes, and implementing appropriate safety management measures. Although legal transportation can effectively reduce accident risks, improve transportation safety, and avoid administrative penalties or reputational losses, it usually requires substantial investment in personnel training, safety management, equipment maintenance, and operational compliance, thereby increasing overall transportation costs. In contrast, enterprises may choose illegal transportation in an attempt to reduce operating costs or maximize short-term economic benefits by violating safety regulations, such as using unqualified vehicles or personnel, neglecting safety inspections, or failing to comply with transportation requirements. However, once such violations are detected or lead to accidents, enterprises may face administrative penalties, economic losses, compensation liabilities, and reputational damage.

Local governments are responsible for supervising hazardous materials transportation activities within their jurisdictions. They may choose either strict regulation or lenient regulation. Under strict regulation, local governments allocate more regulatory resources by increasing the frequency of inspections, strengthening law enforcement, deploying additional supervisory personnel, and imposing stricter penalties on illegal transportation activities. These measures improve the probability of detecting violations and contribute to transportation safety but also result in higher regulatory expenditures. Alternatively, local governments may adopt relatively lenient regulations, which reduce regulatory costs

by decreasing inspection frequency and enforcement intensity. However, insufficient supervision may increase the likelihood of illegal transportation behavior and transportation accidents, thereby undermining public safety and reducing regulatory effectiveness.

2.2. Basic Assumptions

Assumption 1. Local governments (G) and hazardous materials transportation enterprises (C) are assumed to be boundedly rational decision-makers who continuously adjust their strategies according to changes in the external environment. Meanwhile, both parties continuously adjust their strategies in response to changes in the external environment.

Assumption 2. For local governments, the cost of implementing a strict regulatory policy is denoted as D_s , where $D_s > 0$; the cost of implementing a lenient regulatory policy is denoted as D_r , where $D_r > 0$. Obviously, $D_s > D_r$. When illegal transportation behavior is detected, the enterprise is subject to a penalty f , where $f > 0$ (It is assumed that illegal transportation behavior can only be effectively detected under strict regulation).

For hazardous materials transportation enterprises, the cost of choosing legal transportation is denoted as D_l , where $D_l > 0$; the cost of choosing illegal transportation is denoted as D_i , where $D_i > 0$. Obviously, $D_l > D_i$. Upon completing the corresponding transportation task, the enterprise obtains a revenue of R , where $R > 0$.

Assumption 3. The probability that local governments adopt strict regulation is q , while the probability of adopting lenient regulation is $1 - q$. The probability that hazardous materials transportation enterprises choose legal transportation is p , while the probability of choosing illegal transportation is $1 - p$. Clearly, $p, q \in [0, 1]$, and $1 - p, 1 - q \in [0, 1]$.

To facilitate the formulation and analysis of the evolutionary game model, the main symbols and parameters used in this study are summarized in **Table 2**.

2.3. Payoff Matrix

The evolutionary game payoff matrix between local governments and hazardous materials transportation enterprises is shown in **Table 3**.

Table 2. Summary of symbols and parameters used in the evolutionary game model.

Symbol/Parameter	Definition
G	Local governments
C	Hazardous materials transportation enterprises
D_s	Cost of implementing strict regulation by local governments
D_r	Cost of implementing lenient regulation by local governments
f	Fine imposed on hazardous materials transportation enterprises when illegal transportation behaviors are detected
D_l	Cost of adopting legal transportation by hazardous materials transportation enterprises
D_i	Cost of adopting illegal transportation by hazardous materials transportation enterprises
R	Revenue obtained by enterprises upon completion of transportation tasks
q	Probability of local governments adopting strict regulations
p	Probability of hazardous materials transportation enterprises adopting legal transportation
E_p	Expected payoff of hazardous materials transportation enterprises choosing legal transportation
E_{1-p}	Expected payoff of hazardous materials transportation enterprises choosing illegal transportation
E_c	Average expected payoff of hazardous materials transportation enterprises under different strategies
E_q	Expected payoff of local governments choosing strict regulation
E_{1-q}	Expected payoff of enterprises choosing lenient regulation
E_G	Average expected payoff of local governments under different strategies
θ	Transportation safety quality
α	Elasticity coefficient of the influence of local governments' regulatory efforts on hazardous materials transportation enterprises
B	Contribution coefficient of local government regulation to transportation safety quality under the influence of uncontrollable factors

Table 3. The payoff matrix between local governments and hazardous materials transportation enterprises.

Hazardous Materials Transportation enterprises	Local Governments	
	Strict Regulation (q)	Lenient Regulation ($1 - q$)
Legal Transportation (p)	$(R - D_l, -D_s)$	$(R - D_l, -D_r)$
Illegal Transportation ($1 - p$)	$(R - D_i - f, -D_s + f)$	$(R - D_i, -D_r)$

3. Replicator Dynamic Equations and Stability Analysis of the Evolutionary Game

3.1. Replicator Dynamic Equations

Assume that the expected payoffs of hazardous materials transportation enterprises choosing the strategies of “legal transportation” and “illegal transportation” are denoted by E_p and E_{1-p} , respectively, while the average payoff is denoted by E_c . Then:

$$E_p = q(R - D_l) + (1 - q)(R - D_l) \quad (1)$$

$$E_{1-p} = q(R - D_i - f) + (1 - q)(R - D_i) \quad (2)$$

$$E_c = pE_p + (1 - p)E_{1-p} \quad (3)$$

Therefore, according to Equations (1)–(3), the replicator dynamic equation of hazardous materials transportation enterprises $C(p)$ can be expressed as:

$$\begin{aligned} C(p) &= \frac{dp}{dt} = p(E_p - E_c) = \\ &= p[E_p - pE_p - (1 - p)E_{1-p}] = \\ &= p[R - D_l - p(R - D_l) - (1 - p)(R - D_i - qf)] \\ &= p(1 - p)(D_i - D_l + f) \end{aligned} \quad (4)$$

Assume that the expected payoffs of local governments choosing the strategies of “strict regulation” and “lenient regulation” are denoted by E_q and E_{1-q} , respectively, while the average payoff is denoted by E_G . Then:

$$E_q = p(-D_s) + (1 - p)(-D_s + f) \quad (5)$$

$$E_{1-q} = p(-D_r) + (1 - p)(-D_r) \quad (6)$$

$$E_G = qE_q + (1 - q)E_{1-q} \quad (7)$$

Therefore, according to Equations (5)–(7), the replicator dynamic equation of the local governments can be expressed $G(q)$ as:

$$\begin{aligned} G(q) &= \frac{dq}{dt} = q(E_q - E_G) = \\ &= q[E_q - qE_q - (1 - q)E_{1-q}] = \\ &= q[-D_s + f - qf - q(-D_s + f - qf) - \\ &= (1 - q)(-D_r)] = q(1 - q)(D_r - D_s + f - pf) \end{aligned} \quad (8)$$

3.2. Evolutionary Stability Analysis

Proposition 1. For the above evolutionary game system, $X_1 = (0, 0)$, $X_2 = (0, 1)$, $X_3 = (1, 0)$, $X_4 = (1, 1)$ are fixed equilibrium points, while $X_5(p^*, q^*)$ is the interior equilibrium point, where $p^* = \frac{D_r - D_s + f}{f}$, $q^* = -\frac{D_i - D_l}{f}$.

Proof. According to the method proposed by Weinstein^[22], the equilibrium points must satisfy $C(p) = 0$ and $G(q) = 0$. Therefore, $X_1 = (0, 0)$, $X_2 = (0, 1)$, $X_3 = (1, 0)$, $X_4 = (1, 1)$ are fixed equilibrium points, while $X_5(p^*, q^*)$ is the interior equilibrium point. $\square$

Proposition 1 only identifies the equilibrium points of the evolutionary game system. Whether these equilibrium points constitute Evolutionarily Stable Strategies (ESS) requires further investigation.

Corollary 1. For the above equilibrium points, the evolutionary stability analysis is as follows:

1. The boundary equilibrium points X_1, X_2, X_3, X_4 are all unstable.
2. The interior equilibrium point X_5 is also unstable.

Proof. According to the method proposed by Friedman^[23], the evolutionary stability of the replicator dynamic system at the equilibrium points can be determined using the Jacobian matrix. Assume that the Jacobian matrix of this evolutionary game is denoted by J . The corresponding Jacobian matrix is given as follows:

$$J = \begin{Bmatrix} (1 - 2p)(D_i - D_l + qf) & p(1 - p)f \\ -q(1 - q)f & (1 - 2q)(D_r - D_s + f - pf) \end{Bmatrix} \quad (9)$$

By solving the determinant ($\det J$) and the trace ($\text{tr } J$) of the Jacobian matrix at the boundary equilibrium points and the interior equilibrium point, respectively, the results shown in **Table 4** can be obtained.

According to the stability criterion of the evolutionary game model, if the Jacobian matrix satisfies $\det J > 0$ and $\text{tr } J < 0$, then the corresponding evolutionary strategy is an Evolutionarily Stable Strategy (ESS). However, the signs of $\det J$ and $\text{tr } J$ at the four boundary equilibrium points X_1, X_2, X_3, X_4 cannot be determined directly. Moreover, X_5 is a center point, and its stability still requires further analysis. Therefore, Corollary 1 can be obtained.

Table 4. Expressions for the determinant and trace of the equilibrium points.

Equilibrium Point	Determinant/Trace	Expression
$X_1 = (0, 0)$	(det J) (tr J)	$(D_i - D_l)(D_r - D_s + f)$ $(D_i - D_l) + (D_r - D_s + f)$
$X_2 = (0, 1)$	(det J) (tr J)	$-(D_i - D_l + f)(D_r - D_s + f)$ $(D_i - D_l + f) - (D_r - D_s + f)$
$X_3 = (1, 0)$	(det J) (tr J)	$-(D_i - D_l)(D_r - D_s + f)$ $-(D_i - D_l) + (D_r - D_s + f)$
$X_4 = (1, 1)$	(det J) (tr J)	$(D_i - D_l + f)(D_r - D_s)$ $(D_i - D_l + f) - (D_r - D_s)$
$X_5(p^*, q^*)$	(det J) (tr J)	$\frac{(D_r - D_s + f)(D_r - D_s)(D_i - D_l)(D_i - D_l + f)}{f^2}$ 0

□

Proposition 2. When constraints are imposed on the parameters, the evolutionary game system may exhibit multiple Evolutionarily Stable Strategies (ESS).

Case 1: If $(D_r - D_s + f) > 0$ and $(D_i - D_l + f) < 0$, then $(p, q) = (0, 1)$ is an ESS.

Case 2: If $(D_r - D_s + f) < 0$ and $(D_i - D_l + f) > 0$, then $(p, q) = (0, 0)$ is an ESS.

Case 3: If $(D_r - D_s + f) < 0$ and $(D_i - D_l + f) < 0$, then $(p, q) = (0, 0)$ is an ESS.

Case 4: If $(D_r - D_s + f) > 0$ and $(D_i - D_l + f) > 0$, then the system has no ESS.

Proof. According to the basic assumptions in Section 2.2, $(D_i - D_l) < 0$ and $(D_r - D_s) < 0$.

For Case 1, based on $(D_i - D_l) < 0$, $(D_r - D_s) < 0$, as well as $(D_r - D_s + f) > 0$ and $(D_i - D_l + f) < 0$, it can be derived that, at point $X_2 = (0, 1)$, the corresponding $\det J > 0$ and $\text{tr } J < 0$ satisfy the stability conditions. Therefore, $(p, q) = (0, 1)$ is an ESS. □

Similar conclusions can be drawn for the remaining cases.

To more intuitively illustrate the dynamic evolution process of strategy selection between local governments and hazardous materials transportation enterprises, this study employs MATLAB to simulate the evolutionary game trends. The simulation results are shown in **Figures 1–4**.

Since the objective of the simulations is to verify the evolutionary characteristics under different analytical cases rather than reproduce a specific empirical scenario, the parameter values are selected as representative hypothetical values that satisfy the corresponding analytical conditions derived in the stability analysis. Specifically, the parameters are chosen to ensure that the inequalities defining

Cases 1–4 are satisfied while maintaining economically reasonable relationships among regulatory costs, compliance costs, and penalties. In particular, the cost of legal transportation is assumed to be higher than that of illegal transportation ($(D_i - D_l) < 0, D_l > D_i$), reflecting the additional investments required for regulatory compliance, such as safety management, personnel training, and equipment maintenance. Similarly, the cost of strict regulation is assumed to be higher than that of lenient regulation ($(D_r - D_s) < 0, D_s > D_r$), reflecting the additional regulatory resources required for frequent inspections, law enforcement activities, personnel deployment, and administrative supervision. Meanwhile, the fine imposed on enterprises varies across different cases to represent different levels of regulatory deterrence. The initial strategy probabilities are uniformly set as $(p, q) = (0.3, 0.6)$, representing a realistic initial state in which enterprises exhibit a relatively low willingness to comply, whereas local governments initially maintain a relatively high level of regulatory effort.

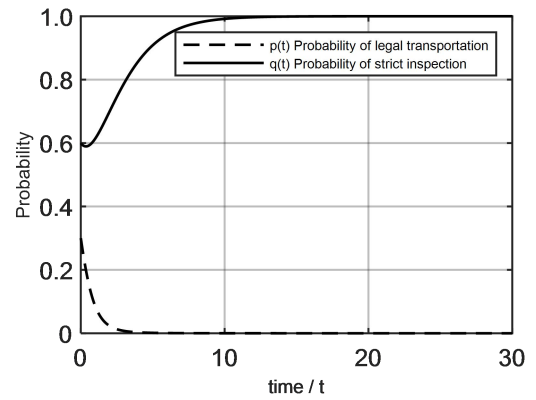


Figure 1. The evolutionary game trend between local governments and hazardous materials transportation enterprises in Case 1.

Note: The parameter settings are as follows^[24,25]: $D_l = 5$; $D_i = 2$; $D_s = 4$; $D_r = 2$; $f = 2.5$; $(p, q) = (0.3, 0.6)$; $T = 30$.

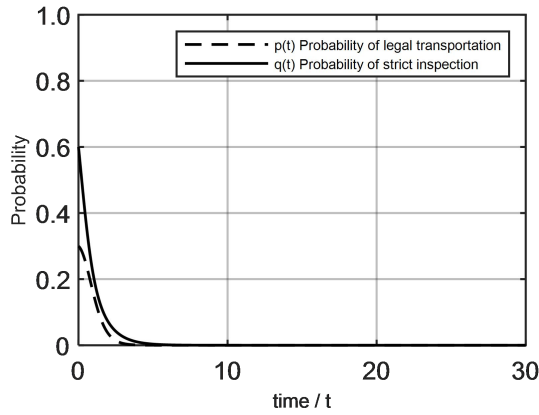


Figure 2. The evolutionary game trend between local governments and hazardous materials transportation enterprises in Case 2.

Note: The parameter settings are as follows^[24,25]: $D_l = 5$; $D_i = 3$; $D_s = 6$; $D_r = 2$; $f = 3$; $(p, q) = (0.3, 0.6)$; $T = 30$.

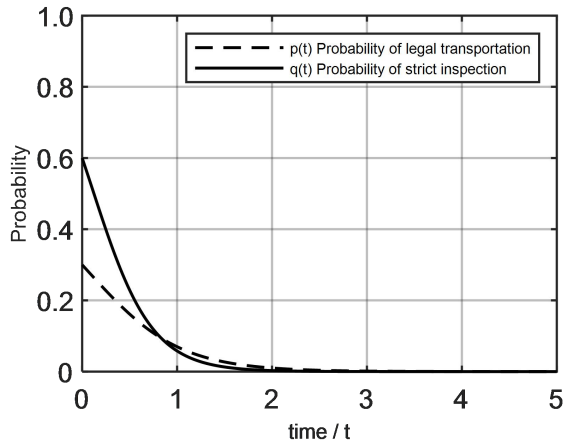


Figure 3. The evolutionary game trend between local governments and hazardous materials transportation enterprises in Case 3.

Note: The parameter settings are as follows^[24,25]: $D_l = 5$; $D_i = 3$; $D_s = 6$; $D_r = 2$; $f = 1$; $(p, q) = (0.3, 0.6)$; $T = 5$.

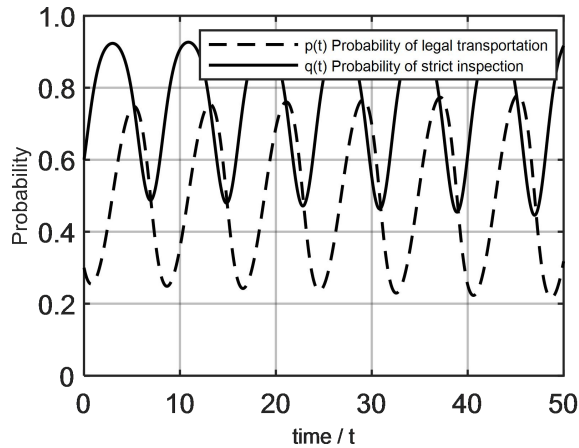


Figure 4. The evolutionary game trend between local governments and hazardous materials transportation enterprises in Case 4.

Note: The parameter settings are as follows^[24,25]: $D_l = 5$; $D_i = 2$; $D_s = 4$; $D_r = 2$; $f = 4$; $(p, q) = (0.3, 0.6)$; $T = 50$.

Based on the above analytical results, under Case 1, the evolutionary game converges to X_2 , indicating that $X_2 = (0, 1)$ is the unique Evolutionarily Stable Strategy (ESS). Since the fine (f) is lower than the additional cost incurred by legal transportation compared with illegal transportation, hazardous materials transportation enterprises are more inclined to take risks and engage in illegal transportation when choosing between “legal transportation” and “illegal transportation.” However, local governments tend to adopt strict regulations. As shown above, although local governments invest substantial human and material resources in safety inspections, the regulatory effect is not significant. Therefore, this outcome is not considered an ideal ESS.

Under Cases 2 and 3, the evolutionary game converges to X_1 , indicating that $X_1 = (0, 0)$ is the unique ESS. In this situation, hazardous materials transportation enterprises tend to choose “illegal transportation,” while local governments tend to adopt “lenient regulation.” Clearly, neither of these two cases represents an ideal ESS.

Under Case 4, there is no ESS between local governments and hazardous materials transportation enterprises, and the strategies of both parties exhibit mutual dependence. This situation is more consistent with the practical reality of hazardous materials transportation safety supervision. Hazardous materials transportation enterprises can hardly ensure fully compliant legal transportation at all times; instead, they choose the strategy that maximizes their own interests by comprehensively considering factors such as transportation costs, the probability of detection, and potential penalties. Similarly, local governments are unable to maintain continuous and comprehensive inspections and usually adopt selective inspection strategies.

At present, the evolutionary game results diverge: when local governments implement strict regulation, the illegal transportation behavior of hazardous materials transportation enterprises decreases rapidly. In this case, the average payoff of the “strict regulation” strategy gradually declines, prompting local governments to adjust their strategies and reduce the frequency of regulation, which in turn leads to an increase in illegal transportation behavior once again.

Therefore, based on Case 4, a dynamic payoff matrix is introduced in an attempt to make the evolutionary game converge to $X_5 = (p^*, q^*)$, thereby identifying a stable evolutionary strategy.

3.3. Sensitivity and Robustness Analysis

Since Case 4 best reflects the practical characteristics of hazardous materials transportation safety regulation, sensitivity analysis is conducted under this case. The penalty parameter f is selected because it represents one of the primary regulatory instruments available to local governments. During the analysis, all other parameters are kept unchanged, while only the value of f is varied to investigate its influence on the evolutionary trajectories. The simulation results are shown in **Figure 5**. As the penalty parameter increases from 3.5 to 5.5, the evolutionary trajectories of both local

governments and hazardous materials transportation enterprises continue to exhibit periodic oscillations, indicating that the qualitative characteristics of the system remain unchanged under different penalty levels. However, the oscillation period decreases as the penalty increases, implying that both participants adjust their strategies more frequently in response to changes in each other's behavior. These results suggest that increasing penalty intensity strengthens the strategic interaction between regulatory enforcement and enterprise decision-making, thereby accelerating the dynamic adjustment process without fundamentally altering the oscillatory evolutionary pattern predicted under Case 4.

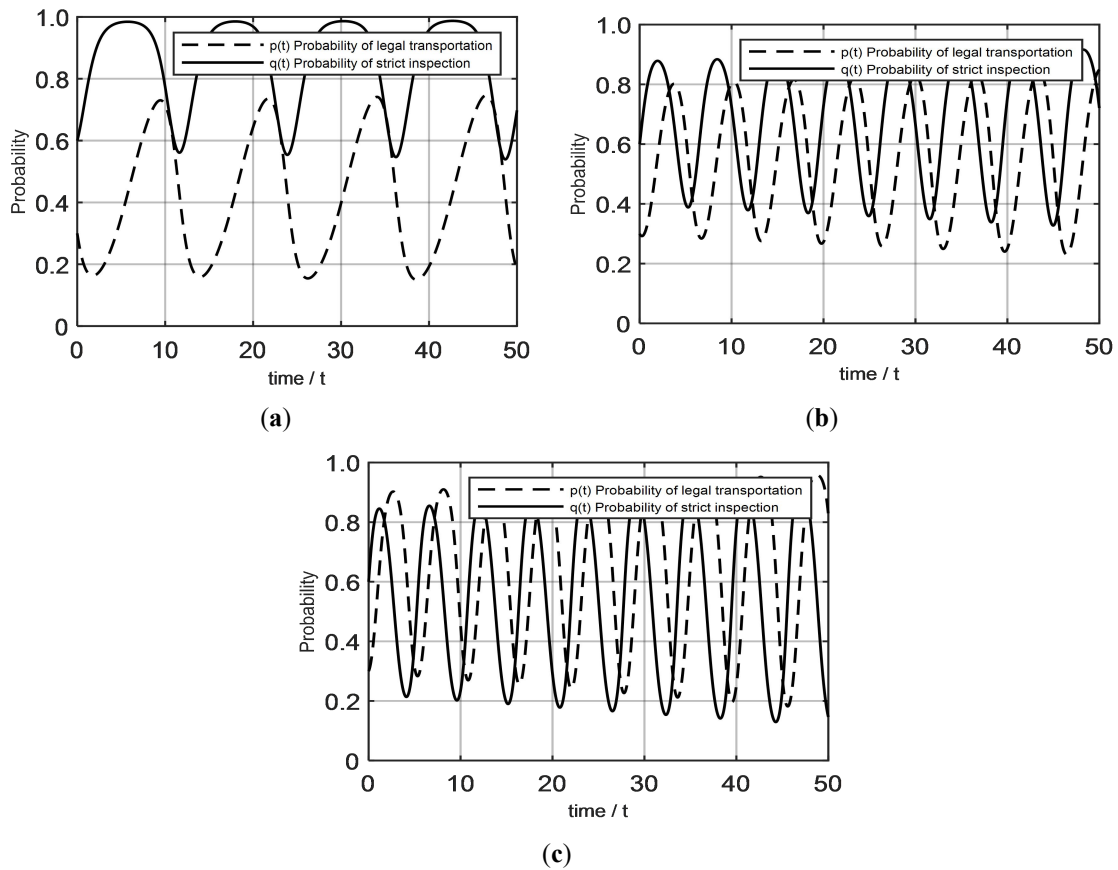


Figure 5. Sensitivity analysis of the penalty parameter f under Case 4: (a) The parameter settings are as follows: $D_l = 5$; $D_i = 2$; $D_s = 4$; $D_r = 2$; $f = 3.5$; $(p, q) = (0.3, 0.6)$; $T = 50$. (b) The parameter settings are as follows: $D_l = 5$; $D_i = 2$; $D_s = 4$; $D_r = 2$; $f = 4.5$; $(p, q) = (0.3, 0.6)$; $T = 50$. (c) The parameter settings are as follows: $D_l = 5$; $D_i = 2$; $D_s = 4$; $D_r = 2$; $f = 5.5$; $(p, q) = (0.3, 0.6)$; $T = 50$.

To further verify the robustness of the proposed model, an alternative set of parameters satisfying the analytical conditions of Case 4 is adopted while keeping the initial strategy probabilities unchanged. The corresponding simulation results are presented in **Figure 6**. It can be observed that,

although the parameter values are changed simultaneously, the evolutionary trajectories of both local governments and hazardous materials transportation enterprises continue to exhibit periodic oscillatory behavior, which is consistent with the theoretical analysis under Case 4. Although slight dif-

ferences in the oscillation characteristics may be observed, the qualitative evolutionary pattern of the system remains unchanged. These results demonstrate that the proposed evolutionary game model is robust to reasonable parameter variations. The qualitative evolutionary behavior remains consistent under different parameter settings, indicating that the main conclusions of this study do not rely on any particular parameter configuration.

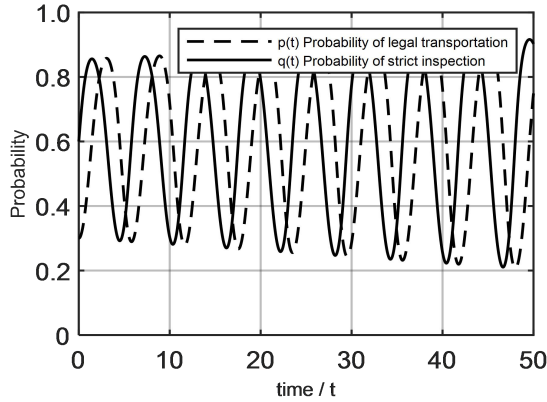


Figure 6. Robustness analysis under an alternative parameter setting satisfying the conditions of Case 4.

Note: The parameter settings are as follows: $D_l = 6$; $D_i = 3$; $D_s = 5$; $D_r = 3$; $f = 5$; $(p, q) = (0.3, 0.6)$; $T = 50$.

4. The Influence of the Higher-Level Government's Assessment Mechanism on the Evolutionarily Stable Strategy

In response to the phenomenon observed in Case 4 of Section 2.2, where the strategies of the evolutionary game system fail to converge and instead exhibit periodic oscillations, this study introduces a dynamic assessment mechanism implemented by higher-level governments into the evolutionary game model between local governments and hazardous materials transportation enterprises. The theoretical rationale for introducing this mechanism is that the strategic behavior of local governments is influenced not only by direct regulatory costs and benefits but also by external performance incentives provided by higher-level governments. Compared with conventional regulatory approaches that mainly rely on fixed penalties and administrative supervision, a dynamic assessment mechanism continuously adjusts the incentives faced by local governments according to their regulatory performance, thereby promoting sustained regulatory effort

and reducing the likelihood of strategic fluctuations. Such a performance-oriented incentive framework has been widely recognized as an effective means of improving regulatory efficiency and long-term governance performance.

Following the theoretical framework proposed by Wang and Shi^[26], this study evaluates the regulatory performance of local governments based on regional transportation safety quality. Accordingly, the production function of regional transportation safety quality presented in the following section is adapted from the model developed by Wang and Shi^[26] and is incorporated into the proposed evolutionary game framework to characterize the dynamic relationship between regulatory effort and transportation safety quality.

Dynamic Assessment Mechanism Oriented Toward Transportation Safety Quality

Higher-level governments evaluate the effectiveness of local governments' supervision of hazardous materials transportation based on improvements in transportation safety quality. Hazardous materials transportation safety is affected by four factors: transportation personnel, transportation vehicles, hazardous materials, and the environment^[27]. Among these factors, transportation personnel, transportation vehicles, and hazardous materials are closely related to the regulatory efforts of local governments, whereas environmental factors (including road conditions and weather conditions during hazardous materials transportation) are uncontrollable factors.

The production function of regional transportation safety quality is defined as follows:

$$\theta = Bq^\alpha \quad (10)$$

where θ represents transportation safety quality, and α denotes the elasticity coefficient of the impact of local governments' regulatory efforts (represented by the probability of strict regulation q) on hazardous materials transportation enterprises, where $\alpha \in [0, 1]$. An increase in the probability of strict regulation generally helps encourage enterprises to engage in legal transportation; however, its marginal effect exhibits a diminishing trend. B represents the regulatory effectiveness coefficient of the government in hazardous materials transportation supervision, where $B \geq 0$.

B represents the contribution of local government regulation to transportation safety quality and reflects the in-

fluence of uncontrollable factors. The larger B is, the more significant the effect of local government regulation on improving transportation safety quality. Conversely, the smaller B is, the weaker the regulatory effect of the government due to interference from other factors.

The marginal effect of government regulatory effort on the improvement of transportation safety quality can be derived as follows:

$$\frac{\partial \theta}{\partial p} = B\alpha q^{\alpha-1} \quad (11)$$

The new dynamic payoff matrix is shown in **Table 5**.

The new replicator dynamic equations are as follows:

$$C(p) = \frac{dp}{dt} = p(E_p - E_C) = p(1-p)(D_i - D_l + f) \quad (12)$$

$$G(q) = \frac{dq}{dt} = q(E_q - E_G) = q(1-q)(D_r - D_s + f + B\alpha q^{\alpha-1} - p(f + B\alpha q^{\alpha-1})) \quad (13)$$

Using this evolutionary game model, simulations of the evolutionary game trends under Case 4 in Section 3.2 are conducted. The simulation results are shown in **Figure 7**.

Table 5. The payoff matrix between the local governments and hazardous materials transportation enterprises under the transport safety and quality-oriented assessment mechanism.

Hazardous Materials Transportation Enterprises	Local Governments	
	Strict Regulation (q)	Lenient Regulation ($1 - q$)
Legal Transportation (p)	$(R - D_l, -D_s)$	$(R - D_l, -D_r)$
Illegal Transportation ($1 - p$)	$(R - D_i - f, -D_s + f + B\alpha q^{\alpha-1})$	$(R - D_i, -D_r)$

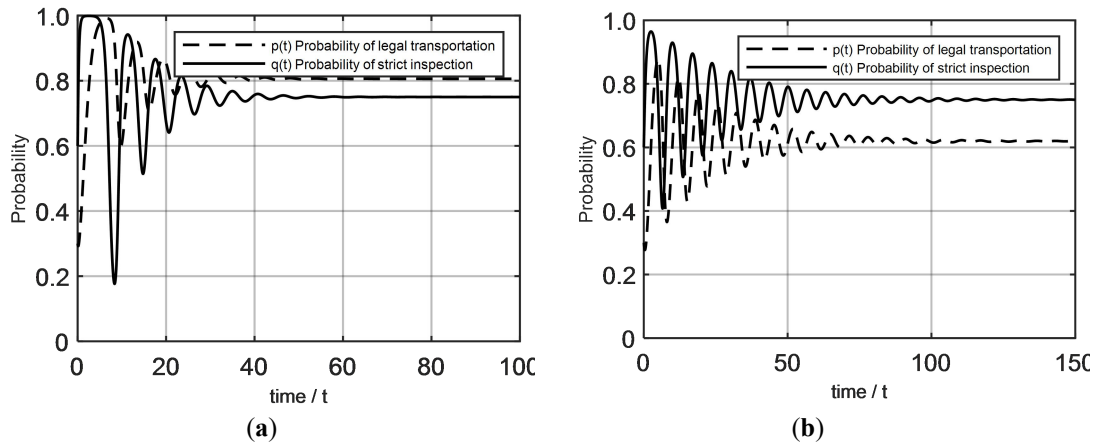


Figure 7. The evolutionary game trend between local governments and hazardous materials transportation enterprises under the transport safety and quality-oriented assessment mechanism: (a) The parameter settings are as follows: $D_l = 5$; $D_i = 2$; $D_s = 4$; $D_r = 2$; $f = 4$; $B = 25$; $(p, q) = (0.3, 0.6)$; $T = 100$; (b) The parameter settings are as follows: $D_l = 5$; $D_i = 2$; $D_s = 4$; $D_r = 2$; $f = 4$; $B = 5$; $(p, q) = (0.3, 0.6)$; $T = 100$.

After introducing the transportation safety quality-oriented dynamic assessment mechanism, the evolutionary game converges to a stable equilibrium. Both local governments and hazardous materials transportation enterprises exhibit a relatively strong willingness to adopt the strategies of “strict regulation” and “legal transportation,” respectively, thereby improving the hazardous materials transportation safety supervision system.

The simulation results further indicate that the effectiveness of the proposed dynamic assessment mechanism

depends critically on the government regulatory effectiveness coefficient. When the government regulatory effectiveness coefficient for hazardous materials transportation B is reduced to one-fifth of its original value, the evolutionary game strategies tend toward stable periodic growth, and enterprises’ willingness to choose legal transportation declines. This finding suggests that the successful implementation of the proposed mechanism in practice may face several challenges. First, differences in regulatory capacity across regions, such as shortages of qualified inspectors, limited financial re-

sources, and uneven enforcement capabilities, may reduce the effectiveness of regulatory actions. Second, external factors beyond the control of local governments, including adverse weather conditions, road infrastructure deficiencies, traffic congestion, and unexpected emergencies, may weaken the actual effectiveness of supervision even when regulatory efforts remain unchanged. Consequently, the dynamic assessment mechanism should be implemented together with supporting measures that enhance regulatory capacity and improve the external transportation environment. Otherwise, assessment results may not accurately reflect the actual regulatory performance of local governments, thereby reducing the incentive effects of the assessment mechanism.

5. Conclusions

This study constructs a two-player evolutionary game model consisting of local governments and hazardous materials transportation enterprises to investigate the dynamic evolution of regulatory and compliance strategies under the existing hazardous materials transportation regulatory system. Unlike traditional game-theoretic models that assume complete rationality, the evolutionary game framework adopted in this study assumes that both participants possess bounded rationality and continuously adjust their strategies through repeated interactions according to changes in costs, benefits, and environmental conditions. Based on the replicator dynamic equations, the Jacobian matrix is employed to analyze the stability of the equilibrium points, while MATLAB simulation experiments are conducted to visualize the dynamic evolutionary process under different parameter settings. The theoretical analysis and simulation results consistently indicate that, under the traditional regulatory mechanism, the evolutionary game system fails to converge to an ideal Evolutionarily Stable Strategy (ESS). Instead, local governments and hazardous materials transportation enterprises remain in a state of continuous strategic adjustment, resulting in cyclical fluctuations rather than long-term stability. Consequently, the regulatory objectives of local governments and the compliance decisions of enterprises cannot be effectively coordinated, limiting the overall effectiveness of hazardous materials transportation safety regulation.

The instability of the traditional regulatory mechanism can be attributed to the conflicting interests of the two par-

ticipants. On the one hand, transportation enterprises seek to maximize economic benefits by reducing operating costs, which may encourage opportunistic behaviors such as illegal transportation when the expected benefits outweigh the potential penalties. On the other hand, local governments are required to allocate considerable financial and administrative resources to maintain strict supervision. Because regulatory resources are limited and enforcement costs remain high, local governments may gradually reduce regulatory intensity if sufficient incentives are absent. Under these circumstances, neither participant has a strong motivation to maintain its socially desirable strategy over the long term, causing the system to evolve repeatedly between different strategic combinations rather than converging to a stable equilibrium. This finding suggests that relying solely on traditional reward-and-punishment mechanisms is insufficient to sustain effective hazardous materials transportation regulation.

To overcome these limitations, this study further introduces a dynamic assessment mechanism oriented toward transportation safety quality. Different from conventional regulatory approaches, this mechanism incorporates the role of higher-level governments by evaluating the regulatory performance of local governments according to improvements in transportation safety quality rather than simply measuring inspection frequency or administrative outputs. In practical implementation, higher-level governments can establish a periodic performance assessment system in which local governments are evaluated using objective indicators related to transportation safety quality, including accident frequency, enterprise compliance rates, regulatory effectiveness, and emergency response capability. The assessment results can then be used by higher-level governments to dynamically adjust the incentives and constraints faced by local governments according to their regulatory performance. This dynamic feedback mechanism encourages local governments to maintain sustained regulatory efforts rather than pursuing short-term administrative targets. As regulatory performance improves, hazardous materials transportation enterprises are subject to more effective supervision and a higher probability of violation detection, thereby increasing the expected cost of illegal transportation. Consequently, the strategic incentives of both local governments and enterprises are continuously adjusted, enabling the evolutionary game system to evolve toward a more stable regulatory equilibrium.

The analytical results demonstrate that the introduction of the transportation safety quality-oriented dynamic assessment mechanism fundamentally changes the evolutionary characteristics of the system. Compared with the traditional regulatory mechanism, the improved model gradually evolves toward a stable evolutionary equilibrium under a wide range of parameter settings. The simulation results further verify that hazardous materials transportation enterprises exhibit a significantly stronger willingness to adopt legal transportation strategies, while local governments become more inclined to maintain strict and standardized supervision. As the strategic choices of both participants gradually stabilize, the frequency of strategic oscillation is substantially reduced, and the overall regulatory system becomes more predictable and efficient. These findings indicate that an appropriately designed assessment mechanism can effectively coordinate the interests of governments and enterprises and promote mutually reinforcing strategic behaviors.

Compared with previous evolutionary game studies on hazardous materials transportation regulation, this study extends the existing literature in two important aspects. First, while most previous studies primarily focus on the stability of boundary equilibrium strategies under static regulatory settings, this study emphasizes the dynamic evolutionary characteristics of the interior equilibrium and demonstrates that the traditional regulatory mechanism may lead to persistent strategic oscillations rather than stable cooperation. Second, by introducing a transportation safety quality-oriented dynamic assessment mechanism involving higher-level governments, this study provides a dynamic incentive framework that effectively improves the stability of regulatory and compliance strategies. These findings are generally consistent with previous studies suggesting that appropriate incentive mechanisms can enhance regulatory effectiveness, while further demonstrating that performance-oriented dynamic assessment plays an important role in promoting long-term strategic coordination between governments and hazardous materials transportation enterprises.

The findings provide several important policy implications. First, higher-level governments should establish a scientific and dynamic performance evaluation system that assesses local governments based on transportation safety quality rather than solely on regulatory inputs or inspection frequency. The assessment should be conducted periodically

using objective safety indicators, such as accident rates, enterprise compliance, and regulatory effectiveness, with the results serving as continuous feedback to guide local governments in adjusting their regulatory strategies and maintaining sustained supervision. Second, the simulation results indicate that the effectiveness of the proposed dynamic assessment mechanism depends critically on the government regulatory effectiveness coefficient. Therefore, local governments should strengthen their regulatory capacity by improving the professional competence of inspectors, increasing the efficiency of law enforcement, and enhancing the application of digital monitoring technologies. At the same time, supporting measures such as improving transportation infrastructure, optimizing transportation routes, and strengthening weather forecasting and emergency response systems should be implemented to reduce the influence of external factors on regulatory effectiveness. Third, regulatory authorities should further integrate the proposed dynamic assessment mechanism with existing administrative supervision, digital monitoring technologies, and information-sharing platforms to improve regulatory efficiency, reduce information asymmetry between regulators and hazardous materials transportation enterprises, and support more effective long-term transportation safety governance.

Despite these contributions, this study has several limitations. First, the MATLAB simulation experiments are conducted using representative hypothetical parameter values that satisfy the analytical conditions of the evolutionary game model, rather than empirical data collected from actual hazardous materials transportation systems. Although these parameter settings are designed to reflect realistic relationships among regulatory costs, compliance costs, and penalties, the simulation results should be interpreted as theoretical demonstrations rather than precise predictions of real-world regulatory behavior. Moreover, the proposed dynamic assessment mechanism has not yet been empirically validated using field data or actual regulatory cases. Consequently, further empirical studies are needed to validate the proposed model and examine the effectiveness of the mechanism under different institutional and regional contexts. Second, to focus on the fundamental strategic interactions underlying hazardous materials transportation safety regulation, this study considers only two participants, namely local governments and hazardous materials transportation enterprises. Although this

simplified framework facilitates theoretical analysis, it does not capture the influence of other important stakeholders, such as emergency management agencies, logistics service providers, and the public, whose interactions may also affect the evolution of regulatory strategies in practice.

Overall, the transportation safety quality-oriented dynamic assessment mechanism proposed in this study not only effectively alleviates strategic conflicts between local governments and hazardous materials transportation enterprises but also promotes stable and rational strategic interactions between both participants. By introducing higher-level governmental incentives into the evolutionary game framework, the proposed mechanism provides an institutional foundation for improving transportation safety governance and enhancing enterprise compliance. Future research may combine the proposed evolutionary game model with empirical accident data, regulatory performance records, or regional panel data to validate the model and estimate its parameters more accurately. In addition, more comprehensive evolutionary game models involving multiple stakeholders, such as emergency management agencies and the public, could be developed to better capture the complexity of hazardous materials transportation safety regulation under real-world conditions.

Author Contributions

Conceptualization, F.S. and Z.L.; methodology, F.S.; software, Z.L.; formal analysis, Z.L.; resources, F.S.; data curation, Z.L.; writing—original draft preparation, Z.L.; writing—review and editing, F.S.; supervision, F.S.; project administration, F.S. Both authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare that there is no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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