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Original Article

CO-GOVERNANCE OF ONLINE CAR-HAILING OPERATION BASED ON PASSENGER FEEDBACK

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Highlights:
- establishes a tripartite evolutionary game model covering passengers, drivers, and ride-hailing platforms;
- simulations show platform oversight boosts can significantly cut drivers' illegal operation chances;
- raising the deposit amount effectively strengthens drivers' respect for the rules;
- enhancing passenger compensation and promotional rewards can raise passenger satisfaction and service quality;
- robust supervision strategies can elevate the platform's social reputation and management efficiency;
- conclusion offers theoretical grounding and innovative co-governance strategies for ride-hailing regulation.

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Abstract. The illegal operation of online car drivers is a recurring issue that has garnered significant societal attention. The literature has investigated this problem primarily from the perspectives of the government, platforms, and drivers, while the mechanisms for co-governance among different stakeholders in addressing illegal online car-hailing operations have received limited focus. Additionally, the role of passengers in the online car-hailing process has not been sufficiently explored, leading to a lack of systematic research conclusions and inherent limitations. To analyse the evolutionary equilibrium strategies of participants under various scenarios and their influencing factors, a tripartite evolutionary game model involving passengers, drivers, and online car-hailing platforms was constructed. The decision-making behaviours of these stakeholders were examined through numerical simulation. The results indicate that by strengthening investigations and addressing illegal behaviours, online car-hailing platforms can significantly reduce the likelihood of drivers' illegal operations. Furthermore, increasing the amount of guarantee deposits can increase drivers' respect for regulations. Additionally, improving passenger satisfaction can be achieved by increasing compensation for participation in co-governance and increasing promotional rewards from platforms, thereby enhancing service quality. Strengthened supervision strategies not only boost platforms' social reputation and management efficiency but also create positive incentives for strict supervision through penalty income. This study provides a theoretical foundation for optimizing the supervision of the online car-hailing industry, emphasizing the critical roles of strict supervision, positive incentives, and public participation in elevating service standards. The findings enrich the theoretical understanding of online car-hailing market supervision and offer innovative co-governance strategies aimed at fostering the healthy development of the online car-hailing market.

Keywords: online car-hailing platform, passenger feedback, co-governance, evolutionary game model, illegal operations.

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1. Introduction

Passengers' travel experiences have improved significantly with the innovative, flexible, and diverse features of online car-hailing services, which have rapidly expanded worldwide through companies such as *Uber* and *Lyft* in the US, *Bolt* in Europe, and *Grab* in Southeast Asia. This trend is particularly strong in China. According to the *2024 China Ride-Hailing Industry Research Report* (BXIT 2024), *2024 Ride-Hailing Industry Development Insights* (SHHIT 2023) and *2024 Automotive Industry Research Report* (Sun 2024), by 2024, the number of online car-hailing users in China will have exceeded 400 million, with over 6.614 million driver licenses issued and a market scale reaching 100 billion ¥. However, as the market expands and the number of users increases, issues such as passenger–driver conflicts, operational traffic accidents, fabricated trips, and cancellations leading to accidents have become more frequent, affecting service quality and increasing consumer concerns. Among these, illegal operations by drivers represent a high proportion of issues, accounting for the most frequent complaints and often resulting in severe harm. Examples include unlicensed driving, price hikes, forced carpooling, and unlawful operations that persist despite prohibitions. These incidents point to gaps in regulatory oversight, indicating a need to standardize market order. Thus, enhancing the oversight and regulation of driver services is crucial for supporting the healthy growth of the online car-hailing market and fostering a stable social environment.

The current literature has investigated illegal operations and oversight of online car-hailing services from several perspectives:

- studies on government regulation indicate that it is a key driver of the industry's ideal development, underscoring the government's essential role in policy formulation and enforcement (Feng, Wang 2020; Yang *et al.* 2022a, 2022b; Zhong *et al.* 2022; Li *et al.* 2022);
- research on online car-hailing platforms has shown that technological innovation and cost control are key to high-quality oversight, with studies highlighting the potential and challenges in improving oversight efficiency and service quality (Wan *et al.* 2022; Sun *et al.* 2019; You, Zhang 2024);
- from the perspective of drivers, studies have emphasized that service quality is crucial for industry growth, with findings showing that dynamic pricing, driver preferences, and working conditions affect driver safety and satisfaction, suggesting the need for policy and monitoring (Yang *et al.* 2023; Garg, Nazerzadeh 2022; Hong *et al.* 2020; Jaydarifard *et al.* 2024; Mao *et al.* 2021);
- some scholars, taking a multi-stakeholder view, have proposed that balancing innovation and compliance is possible through cooperative policy-making among the government, traditional taxi platforms, and car rental companies, promoting sustainable development (Flores, Rayle 2017; Yang *et al.* 2022a, 2022b; Xing 2024).

Overall, while illegal operations and regulatory responses have been widely examined, several gaps remain:

- existing studies often do not fully consider the interaction and coordination among various governing bodies. Single-perspective studies, which focus on the government, platforms, or drivers alone, may overlook co-governance potential, limiting the practical effectiveness and adaptability of regulatory strategies;
- although some preliminary studies explore government-driver and platform-driver relationships via evolutionary game theory, they often remain limited to 2-party models and fail to analyse the influence of passenger involvement, which is an essential stakeholder in the market.

Online car-hailing oversight is a complex, dynamic system involving multiple stakeholders, requiring more than just one group's regulation. Passengers, as direct service beneficiaries, are also key contributors to co-governance. By providing feedback, lodging complaints, and engaging in discussions, passengers directly influence the business practices of online car-hailing services. As registered users of these platforms, passengers participate in oversight primarily through platform mechanisms, suggesting that passenger–platform cooperation is vital for improving oversight efficiency and optimizing service quality. This cooperation better integrates passenger feedback, encourages driver monitoring by platforms, and contributes to the healthy growth of the online car-hailing market.

Considering the issues in service and operations, this study constructs a tripartite evolutionary model (drivers, passengers, and platforms) to analyse the behavioural decisions and interactions among stakeholders, as each aims to maximize their interests. This study offers 2 main contributions:

- by incorporating the role of passengers in co-governance evaluation, a tripartite evolutionary game model is proposed, which presents a new perspective on stakeholder interactions in the online car-hailing market;
- this study analyses each stakeholder's decision-making process and the event-dependent dynamics of their interactions, providing a novel theoretical framework and analysis method for operational challenges in the online car-hailing industry.

The structure of this study is as follows. Current Section 1 – an introduction. Section 2 reviews the literature on supervision and co-governance in online car-hailing. Section 3 outlines parameter assumptions for drivers, passengers, and platforms and establishes a payoff matrix followed by stability analysis of individual participants and system stability analysis. Section 4 assigns values to parameters and performs simulation analysis. Section 5 discusses the stability and simulation analysis results from Sections 3 and 4. In the Section 6, this study summarizes the research conclusions, management implications, and research limitations and perspectives.

2. Literature review

2.1. Supervision of online car-hailing operations

To supervise the operation of online car-hailing services, research has examined perspectives from the government, platforms, drivers, and passengers, either independently or in collaboration:

- ***government***: Feng & Wang (2020) analysed the influence of government oversight on the online car-hailing market and suggested that governmental bodies adjust oversight strategies and delegate more responsibility to platforms to enhance regulation. Yang *et al.* (2022a, 2022b) examined a supervisory system involving local governments and platforms and identified optimal subsidy and supervision cost ratios that positively affect revenue and service quality, emphasizing the role of scientific supervision in maintaining market order. Zhong *et al.* (2022) argued that government strategies should adapt to market supply and demand, social impact, and stakeholder needs to optimize industry operations. Li *et al.* (2022) highlighted the necessity of government oversight, noting the importance of policy-making in industry governance;

- ***online car-hailing platforms***: Wan *et al.* (2022) emphasized blockchain technology's potential to improve platform supervision, suggesting that increased supervision costs and penalties could standardize the industry. Sun *et al.* (2019) analysed regulatory requirements for platforms in the digital environment, proposing cost-reduction and penalty-increase strategies to align platforms better with regulatory expectations. You & Zhang (2024) argued that platform participation in governance improves regulation quality, noting that digital barriers necessitate cooperative governance;
- ***online car drivers***: Yang *et al.* (2023) explored how drivers' engagement modes impact both their choices and platform operations, helping platforms understand the effects of participation on driver behaviour. Garg & Nazerzadeh (2022) examined the role of dynamic pricing in promoting fair payments and reported that it influences service quality and driver satisfaction. Hong *et al.* (2020) stressed that addressing drivers' concerns about working conditions can stabilize service supply and improve regulatory adherence. Jaydarifard *et al.* (2024) noted that driver fatigue impacts driver behaviour, emphasizing that policies should consider passenger safety and driver health by regulating work hours. Mao *et al.* (2021), in a study of 180000 drivers, reported that prolonged driving increases accident risk, underscoring the importance of ongoing supervision and safety evaluations;
- ***multisubject***: Flores & Rayle (2017) reported that the government, regulatory bodies, and taxi platforms in San Francisco (US) actively support the growth of the online car-hailing sector to foster healthy development. Yang *et al*. (2022a, 2022b) proposed a supervision system involving local governments, platforms, and drivers, recommending that the central government provide tax breaks and subsidies to support local regulatory efforts and enhance service input from drivers. Xing (2024) explored factors influencing compliance within the online car-hailing sector from the perspectives of drivers, platforms, and car rental companies.

In summary, existing studies cover various aspects of online car-hailing supervision, including government policies, platform responsibilities, and driver behaviour, but the role of passengers remains underexplored. Research has yet to fully examine how passenger participation impacts the regulatory landscape and overall industry development.

2.2. Co-governance

Co-governance is a governance concept and model that emphasizes joint participation by the government, the market, social organizations, individual citizens, and other stakeholders in decision-making and the oversight of public affairs. Van Buuren (2009) analysed how cognitive diversity among participants affects co-governance and discussed strategies for integrating these viewpoints to foster inclusive and effective governance. Certomà *et al.* (2020) studied the role of informal practices, such as urban gardening, in governing public spaces. In particular, their work on Rome's Energy Park (Italy) illustrated how multi-stakeholder coordination reshaped decision-making and supported sustainable, inclusive urban development. Using a systematic review approach, Parsons *et al.* (2021) highlighted the current status and challenges of indigenous participation in ocean governance, emphasizing the importance of co-governance, collaborative governance, and environmental justice for global equity. They also identified gaps in the literature related to gender and geographic diversity. Weiand *et al.* (2021) highlighted the need for cross-departmental and interdisciplinary collaboration in ocean environmental governance, exploring cases that reveal challenges in meeting sustainable development goals and strategies to increase governance effectiveness. Similarly, Edge *et al.* (2019) examined food safety governance, emphasizing that effective cooperation among stakeholders requires attention to communication, resource sharing, demand alignment, and inclusivity. Cho *et al.* (2025), through the case of the Food Policy Commission, revealed that network density, diversity, and inclusiveness are key elements of effective co-governance. Poliak *et al.* (2020) argue that the regulatory framework for autonomous vehicles necessitates a multi-stakeholder approach, involving government rule-setting, corporate data-sharing, and public participation.

On the basis of the above literature, co-governance is applicable across fields such as urban planning, environmental protection, public health, education, and traffic management, offering a pathway to address complex social issues in modern governance. Co-governance facilitates the integration of diverse perspectives, enhances inclusivity and effectiveness, and has shown value in sectors such as urban planning and environmental protection. This study takes inspiration from co-governance frameworks to explore a collaborative model for the online car-hailing industry, aiming to develop more comprehensive and effective regulatory strategies for platforms.

In summary, the literature on online car-hailing supervision addresses various perspectives, including the government, platforms, and drivers, and suggests multidimensional strategies such as technological innovation, cost control, service quality, and safety. However, much of this research emphasizes single perspectives and lacks a comprehensive analysis of multi-stakeholder co-governance. The mechanisms of collaboration among stakeholders also remain insufficiently explored. This study, therefore, integrates the needs and roles of different stakeholders through a co-governance approach, constructing a comprehensive supervision framework. Using evolutionary game theory, it systematically analyses interactions among participants and proposes a coordinated supervision strategy to support the healthy, sustainable development of the online car-hailing industry.

3. Methodology

3.1. Problem description

Co-governance is a governance model that emphasizes the participation of multiple stakeholders in decision-making and oversight. In online car-hailing, key stakeholders include passengers, drivers, and platforms. Passengers play dual roles: they act as supervisors by reporting drivers' illegal actions and as supporters of compliant driving practices. Through active engagement in co-governance, passengers help prevent and reduce drivers' illegal activities, contributing to safer and more efficient rides. Moreover, drivers provide services under the oversight of platforms, which connect passengers with available drivers, facilitating transactions and ensuring service reliability.

However, owing to limitations in supervision costs and resources, platforms may struggle to promptly detect and address driver violations. Here, passenger participation becomes crucial; their feedback and reports alert platforms to issues, facilitating quicker resolutions. When illegal driver behaviour becomes more frequent, it can harm relevant stakeholders' interests even if it does not yet pose a broad social threat. Therefore, this study incorporates passengers' roles in co-governance to analyse their effects on online car-hailing operations. A theoretical model was developed to explore participant behaviour and interactions, aiming to identify strategies that support system stability and industry growth. Figure 1 illustrates the relationships among the 3 key parties:

- ***online car-hailing platform and passengers***: the platform offers passengers a convenient travel solution, arranging suitable drivers upon receiving passenger requests and ensuring seamless transactions. Platforms are also responsible for social accountability, passenger safety, service quality, and protection of passengers' rights;
- ***online car-hailing platform and drivers***: platforms coordinate by matching passenger demand with driver availability via algorithms, managing driver services, and monitoring performance. Drivers, in turn, provide travel services according to platform-assigned tasks;
- ***passengers and drivers***: drivers transport passengers from the starting point to the endpoint, whereas passengers, as service recipients, assess the experience. Passengers place travel requests through the platform, and drivers fulfil these requests. After the trip, passengers can rate the driver's service through the platform's feedback system.

This study applies co-governance concepts, evolutionary game theory, and dynamic evolutionary analysis to examine the strategic interactions among stakeholders in the online car-hailing market and how these interactions influence the system's evolution. Through this approach, the study aims to provide a deeper understanding of the operational mechanisms of the online car-hailing market, offering theoretical and practical insights for the healthy development of the industry.

3.2. Model assumptions

Assumption 1. This study involves 3 participants: passengers, drivers, and online car-hailing platforms. It assumes that the information in this tripartite game is not completely symmetrical and that bounded rationality is present. The strategy space of drivers is S_1 = (*compliance operation*, *illegal operation*), that of passengers is S_2 = (*participation in co-governance*, *nonparticipation in co-governance*), and that of online car-hailing platforms is S_3 = (*strong supervision*, *weak supervision*).

Assumption 2. The probability for drivers to select the compliance operation strategy is x and that for them to choose the illegal operation strategy is 1 – *x*; the probability for passengers to choose to participate in co-governance is y and that for them to choose not to participate in co-governance is 1 – *y*; the probability for online car-hailing platforms to choose the strong supervision strategy is *z* and that for them to select the weak supervision strategy is 1 – *z*, and $x, y, z \in [0, 1]$. When the strategy of one stakeholder is adjusted, the other 2-parties will adjust their own strategies accordingly.

Assumption 3. The revenue of drivers from participation in compliance operations is R_1, the revenue from illegal operations is R_2, and $R_1 < R_2$; the cost paid by drivers for compliance operations is C_1, the cost paid for illegal operations is C_2, and $C_1 > C_2$; when passengers participate in co-governance, the positive reputation revenue acquired by drivers in the case of compliance operations is R_3, and the negative reputation loss is R_4; when drivers choose illegal operations and passengers participate in co-governance , drivers need to pay the online car-hailing platform a guarantee deposit *K* as a penalty after the illegal operation is identified by the platform.

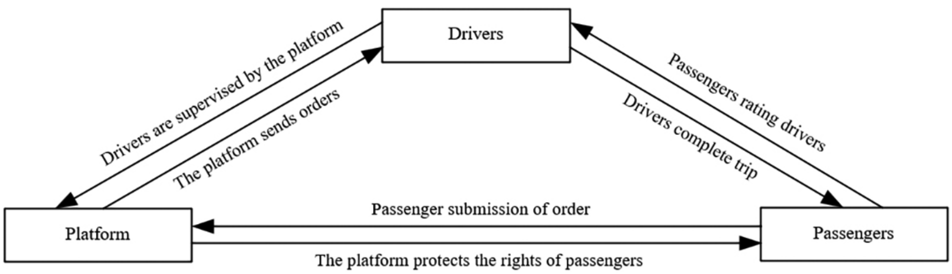

Figure 1. Tripartite logical relation graph

Assumption 4. Enjoying the riding service, passengers acquire revenue of R_5; the cost paid by passengers to enjoy the service is C_3; when passengers participate in co-governance , online car-hailing platforms will give a reward of D to passengers for the sake of promotion; when passengers participate in co-governance , the cost to be paid is C_4, and $D > C_4$; when drivers select illegal operation, the loss suffered by passengers is S; when drivers operate illegally and this is successfully determined by the platform, the compensation given by the online car-hailing platform to passengers is B.

Assumption 5. The revenue obtained by a platform adopting strong supervision is R_6, and that of the platform choosing weak supervision is R_7; the cost paid by the platform adopting strong supervision is C_5, and that paid by the platform choosing weak supervision is C_6, and $C_5 > C_6$; when passengers participate in co-governance, the social reputation revenue acquired by the online car-hailing platform through investigating and treating drivers' illegal operation is R_8, and the corresponding cost is C_7.

Assumption 6. When passengers participate in co-governance, the rate of success achieved by the online car-hailing platform in investing and treating drivers' illegal operations in the case of strong supervision is θ and that in the case of weak supervision is β, and $\theta > \beta$.

Assumption 7. When an online car-hailing platform successfully investigates and addresses a driver's illegal operation, the passenger receives compensation, and the driver is required to pay a guarantee deposit to the platform. Typically, this deposit is set higher than the passenger compensation to deter future violations. The deposit functions as a punitive measure designed to discourage illegal actions by being set at a level that is substantial enough to have a deterrent effect. In contrast, passenger compensation is generally determined by the potential losses the passenger may incur due to the driver's actions, making it relatively smaller. Thus, $K > B$ by default.

Assumption 8. When an online car-hailing platform incurs costs to investigate and manage driver misconduct, it also gains social reputation benefits by maintaining market order and improving service quality. The comparison between the cost C_7 and the reputation gain R_8 is complex, as they represent different aspects: C_7 covers resources and cost input by the platform into investigating and treating illegal behaviours, such as technology, manpower, and time spent on addressing illegal behaviours, whereas R_8 reflects the enhanced social reputation and positive evaluations the platform gains through effective regulation, which supports long-term brand development and user trust. While C_7 may appear substantial in the short term, the reputation benefits R_8 contribute significantly to the platform's market competitiveness, helping to attract more users and drivers and, ultimately, increasing revenue. Therefore, the long-term effect of R_8 is often expected to exceed C_7, making $R_8 > C_7$ by default.

On the basis of these hypotheses, the decision-making behaviours of drivers, passengers, and online car-hailing platforms were integrated into relevant variables (Table 1). Additionally, a model payoff matrix was constructed (Table 2), where the parameter values represent each party's payoff under various strategy combinations.

3.3. Modelling

According to the above hypotheses and parameter settings, a payoff matrix of online car drivers, passengers and online car-hailing platforms was established, as shown in Table 2.

3.4. Analysis of the evolutionary equilibrium strategy

3.4.1. Strategy stability analysis of online car drivers

The expected revenues v_{11} and v_{12} of online car drivers under compliance operation and illegal operation strategies, as well as the corresponding average expected revenue v_1, can be acquired via Equation (3). The probability for drivers to choose the compliance operation strategy is x, the probability for them to select the illegal operation strategy is $1 - x$, and $0 \le x \le 1$.

$$\begin{aligned} v_{11} &= y \cdot z \cdot (R_1 - C_1 + R_3) + \\ & z \cdot (1-y) \cdot (R_1 - C_1) + \\ & y \cdot (1-z) \cdot (R_1 - C_1 + R_3) + \\ & (1-z) \cdot (1-y) \cdot (R_1 - C_1 + R_3); \end{aligned} \tag{1}$$

$$\begin{aligned} v_{12} &= y \cdot z \cdot (R_2 - C_2 - R_4 - K \cdot \theta) + \\ & z \cdot (1-y) \cdot (R_2 - C_2) + \\ & y \cdot (1-z) \cdot (R_2 - C_2 - R_4 - K \cdot \beta) + \\ & (1-z) \cdot (1-y) \cdot (R_2 - C_2); \end{aligned} \tag{2}$$

$$v_1 = x \cdot v_{11} + (1-x) \cdot v_{12}. \tag{3}$$

Therefore, the replicator dynamics equation of passengers and its 1st-order derivative with respect to x can be obtained as follows:

$$\begin{aligned} F(x) &= -x \cdot (x - 1) \cdot (C_2 - C_1 + R_1 - \\ & R_2 + R_3 + R_4 \cdot y - R_3 \cdot z + K \cdot \beta \cdot y + \\ & R_3 \cdot y \cdot z + K \cdot \theta \cdot y \cdot z - K \cdot \beta \cdot y \cdot z); \end{aligned} \tag{4}$$

$$\begin{aligned} F'(x) &= (1 - 2 \cdot x) \cdot (C_2 - C_1 + R_1 - \\ & R_2 + R_3 + R_4 \cdot y - R_3 z + K \cdot \beta \cdot y + \\ & R_3 \cdot y \cdot z + K \cdot \theta \cdot y \cdot z - K \cdot \beta \cdot y \cdot z). \end{aligned} \tag{5}$$

For convenience of expression, we set:

$$\begin{aligned} G(y) &= C_2 - C_1 + R_1 - R_2 + R_3 + \\ & R_4 \cdot y - R_3 z + K \cdot \beta \cdot y + R_3 \cdot y \cdot z + \\ & K \cdot \theta \cdot y \cdot z - K \cdot \beta \cdot y \cdot z. \end{aligned}$$

Table 1. Symbol description

Symbol	Description
B	in case of passengers' participation in co-governance, when drivers operate illegally and this is successfully determined by the platform, the compensation given by the online car-hailing platform to passengers is B
C_1	the cost paid by drivers for compliance operation is C_1
C_2	the cost paid by drivers for illegal operation is C_2, and $C_1 > C_2$
C_3	the cost paid by passengers when enjoying the service is C_3
C_4	when passengers participate in co-governance, the cost to be paid is C_4, and $D > C_4$
C_5	the cost paid by the platform adopting strong supervision is C_5
C_6	the cost paid by the platform choosing weak supervision is C_6, and $C_5 > C_6$
C_7	when passengers participate in co-governance, the cost paid by the online car-hailing platform through investigating and treating drivers' illegal operation is C_7
D	when passengers participate in co-governance, the reward that will be provided by the online car-hailing platform to passengers is D for the sake of promotion
K	when drivers choose illegal operation and passengers participate in co-governance, drivers need to pay the online car-hailing platform a guarantee deposit K as the penalty
R_1	the revenue of drivers from participation in compliance operation is R_1
R_2	the revenue of drivers from illegal operation is R_2, and $R_1 < R_2$
R_3	when passengers participate in co-governance, the positive reputation revenue acquired by drivers in case of compliance operation is R_3
R_4	when passengers participate in co-governance, the negative reputation loss suffered by drivers due to illegal operation is R_4
R_5	the revenue acquired by passengers when enjoying the service is R_5
R_6	the revenue obtained by a platform adopting strong supervision is R_6
R_7	the revenue acquired by the platform choosing weak supervision is R_7
R_8	when passengers participate in co-governance, the social reputation revenue acquired by the online car-hailing platform through investigating and treating drivers' illegal operation is R_8
S	when drivers choose illegal operation, the loss suffered by passengers is S
x	the probability for drivers to choose the compliance operation strategy is x, the probability for them to select the illegal operation strategy is $1 - x$, and $0 \le x \le 1$
y	the probability for passengers to choose to participate in co-governance is y and that for them to choose not to participate in co-governance is $1 - y$, and $0 \le y \le 1$
z	the probability for online car-hailing platforms to choose the strong supervision strategy is z and that for them to select the weak supervision strategy is $1 - z$, and $0 \le z \le 1$
β	when passengers participate in co-governance, the rate of success achieved by the online car-hailing platform in investing and treating drivers' illegal operation in case of weak supervision is β, and $\theta > \beta$
θ	when passengers participate in co-governance, the rate of success achieved by the online car-hailing platform in investing and treating drivers' illegal operation in case of strong supervision is θ and that in case of weak supervision is β, and $\theta > \beta$

Table 2. Payoff matrix

	Platform's strong supervision z		Platform's weak supervision $1 - z$	
	Passenger participation in co-governance y	Passenger nonparticipation in co-governance $1 - y$	Passenger participation in co-governance y	Passenger nonparticipation in co-governance $1 - y$
Drivers' compliance operation x	$R_1 - C_1 + R_3$	$R_1 - C_1$	$R_1 - C_1 + R_3$	$R_1 - C_1$
	$R_5 - C_3 + D - C_4$	$R_5 - C_3$	$R_5 - C_3 + D - C_4$	$R_5 - C_3$
	$-D + R_6 - C_5$	$R_6 - C_5$	$R_7 - C_6 - D$	$R_7 - C_6$
Drivers' illegal operation $1 - x$	$R_2 - C_2 - R_4 - K \cdot \theta$	$R_2 - C_2$	$R_2 - C_2 - R_4 - K \cdot \beta$	$R_2 - C_2$
	$R_5 - C_3 + D - C_4 - S + B \cdot \theta$	$R_5 - C_3 - S$	$R_5 - C_3 + D - C_4 - S + B \cdot \beta$	$R_5 - C_3 - S$
	$(R_8 - C_7 + K - B) \cdot \theta - D + R_6 - C_5$	$R_6 - C_5$	$(R_8 - C_7 + K - B) \cdot \beta - D + R_7 - C_6$	$R_7 - C_6$

According to the stability theorem of differential equations, the probability for online car-hailing drivers to choose compliance operations can be stable if $F(x)=0$ and $F'(x)<0$. As such, $y^*=\frac{C_1-C_2+R_2-R_1-R_3+R_3\cdot z}{R_4+K\cdot\beta+R_3\cdot z+K\cdot\theta\cdot z-K\cdot\beta\cdot z}$ can be obtained. $G(y)=0$.

Proposition 1: When $y=y^*$, all x are constantly the evolutionary stability strategy; when $y>y^*$, $x=1$ is the evolutionary stability strategy; and when $y<y^*$, $x=0$ is the evolutionary stability strategy.

Proof 1: $G(y)$ is an increasing function according to $G'(y)>0$. When $y=y^*$, $G(y)=0$, $F(x)=0$, and $F'(x)=0$, all x are in a stable state; when $y<y^*$, $G(y)<0$, $F'(x)<0$, $1-2\cdot x>0$ and $x<0.5$, and $x=0$ is the evolutionary stability strategy in this case; when $y>y^*$, $G(y)>0$, $F'(x)<0$, $1-2\cdot x<0$ and $x>0.5$, and $x=1$ is the evolutionary stability strategy under this circumstance.

Proposition 1 indicates that when the probability of passengers choosing to participate in co-governance is y^*, online car-hailing drivers maintain the initial strategy; when this probability is greater than y^*, drivers tend to select compliance operations as the evolutionary stability strategy; and when the probability is smaller than y^*, drivers are inclined to engage in illegal operations as the evolutionary stability strategy.

3.4.2. Strategy stability analysis of passengers

The expected revenues v_{21} and v_{22} of drivers under compliance operation and illegal operation strategies as well as the corresponding expected revenue v_2 can be solved via Equation (8). The probability for passengers to choose to participate in co-governance is y and that for them to choose not to participate in co-governance is 1 – y, and $0\le y\le 1$.

$$v_{21}=x\cdot z\cdot(R_5-C_3+D-C_4)+ z\cdot(1-x)\cdot(R_5-C_3+D-C_4-S+B\cdot\theta)+ x\cdot(1-z)\cdot(R_5-C_3+D-C_4)+ (1-z)\cdot(1-x)\cdot(R_5-C_3+D-C_4-S+B\cdot\beta); \quad (6)$$

$$v_{22}=x\cdot z\cdot(R_5-C_3)+ z\cdot(1-x)\cdot(R_5-C_3-S)+ x\cdot(1-z)\cdot(R_5-C_3)+ (1-z)\cdot(1-x)\cdot(R_5-C_3-S); \quad (7)$$

$$v_2=y\cdot v_{21}+(1-y)\cdot v_{22}. \quad (8)$$

Therefore, the replicator dynamics equation of the drivers and its 1st-order derivative about y are as follows:

$$F(y)=y\cdot(y-1)\cdot(C_4- D-B\cdot\beta+B\cdot\beta\cdot x+B\cdot\beta\cdot z- B\cdot\theta\cdot z+B\cdot\theta\cdot x\cdot z-B\cdot\beta\cdot x\cdot z); \quad (9)$$

$$F'(y)=(2\cdot y-1)\cdot(C_4- D-B\cdot\beta+B\cdot\beta\cdot x+B\cdot\beta\cdot z- B\cdot\theta\cdot z+B\cdot\theta\cdot x\cdot z-B\cdot\beta\cdot x\cdot z). \quad (10)$$

For convenience of expression, we set:

$$H(x)=C_4-D-B\cdot\beta+ B\cdot\beta\cdot x+B\cdot\beta\cdot z-B\cdot\theta\cdot z+ B\cdot\theta\cdot x\cdot z-B\cdot\beta\cdot x\cdot z.$$

According to the stability theorem of differential equations, the probability for passengers to choose co-governance can be stable if $F(y)=0$ and $F'(y)<0$. $x^*=\frac{D-C_4}{B\cdot\beta+B\cdot\theta\cdot z-B\cdot\beta\cdot z}+1$ can be acquired on the basis of $H(x)=0$.

Proposition 2: When $x=x^*$, all y are constantly the evolutionary stability strategy; when $x<x^*$, $y=1$ is the evolutionary stability strategy; and when $x>x^*$, $y=0$ is the evolutionary stability strategy.

Proof 2: $H(x)$ is an increasing function according to $H'(x)>0$. When $x=x^*$, $H(x)=0$, $F(y)=0$ and $F'(y)=0$, all y are under a stable state in this case; when $x>x^*$, $H(x)>0$, $F'(y)<0$, $2\cdot y-1<0$, $y<0.5$, and $y=0$ constitute the evolutionary stability strategy under this circumstance; and when $x<x^*$, $H(x)<0$, $F'(y)<0$, $2\cdot y-1>0$, $y>0.5$, and $y=1$ constitute the evolutionary stability strategy in this case.

Proposition 2 reflects that when the probability for online car-hailing drivers to choose compliance operation is x^*, passengers will stick to the initial strategy; when the probability is greater than x^*, passengers will choose the strategy of participating in co-governance; and when the probability is smaller than x^*, passengers will choose not to participate in co-governance .

3.4.3. Strategy stability analysis of online car-hailing platforms

The expected revenues v_{31} and v_{32} of passengers when they are participating and not participating in co-governance as well as the corresponding expected revenue v_3 can be solved via Equation (13). The probability for online car-hailing platforms to choose the strong supervision strategy is z and that for them to select the weak supervision strategy is 1 – z, and $0\le z\le 1$.

$$v_{31}=x\cdot y\cdot(-D+R_6-C_5)+ x\cdot(1-y)\cdot(R_6-C_5)+ (1-y)\cdot(1-x)\cdot(R_6-C_5)+ y\cdot(1-x)\cdot(-D+R_6-C_5+ (R_8-C_7)\cdot\theta+K\cdot\theta-B\cdot\theta); \quad (11)$$

$$v_{32}=x\cdot y\cdot(-D+R_7-C_6)+ x\cdot(1-y)\cdot(R_7-C_6)+ (1-y)\cdot(1-x)\cdot(R_7-C_6)+$$

$$y \cdot (1-x) \cdot \big(-D + R_7 - C_6 +$$
$$\big(R_8 - C_7\big) \cdot \beta + K \cdot \beta - B \cdot \beta\big); \quad (12)$$

$$v_3 = z \cdot v_{31} + (1-z) \cdot v_{32}. \quad (13)$$

Therefore, the replicator dynamics equation of online car-hailing platforms and its 1t-order derivative about z are as follows:

$$F(z) = z \cdot (z-1) \times$$
$$\big(C_5 - C_6 - R_6 + R_7 - B \cdot \beta \cdot y -$$
$$C_7 \cdot \beta \cdot y + K \cdot \beta \cdot y + R_8 \cdot \beta \cdot y +$$
$$B \cdot \theta \cdot y + C_7 \cdot \theta \cdot y - K \cdot \theta \cdot y -$$
$$R_8 \cdot \theta \cdot y - R_8 \cdot \beta \cdot x \cdot y - B \cdot \theta \cdot x \cdot y -$$
$$C_7 \cdot \theta \cdot x \cdot y + K \cdot \theta \cdot x \cdot y + R \cdot \theta \cdot x \cdot y +$$
$$B \cdot \beta \cdot x \cdot y + C_7 \cdot \beta \cdot x \cdot y - K \cdot \beta \cdot x \cdot y\big); \quad (14)$$

$$F'(z) = (2 \cdot z - 1) \times$$
$$\big(C_5 - C_6 - R_6 + R_7 - B \cdot \beta \cdot y -$$
$$C_7 \cdot \beta \cdot y + K \cdot \beta \cdot y + R_8 \cdot \beta \cdot y +$$
$$B \cdot \theta \cdot y + C_7 \cdot \theta \cdot y - K \cdot \theta \cdot y -$$
$$R_8 \cdot \theta \cdot y - R_8 \cdot \beta \cdot x \cdot y - B \cdot \theta \cdot x \cdot y -$$
$$C_7 \cdot \theta \cdot x \cdot y + K \cdot \theta \cdot x \cdot y + R_8 \cdot \theta \cdot x \cdot y +$$
$$B \cdot \beta \cdot x \cdot y + C_7 \cdot \beta \cdot x \cdot y - K \cdot \beta \cdot x \cdot y\big). \quad (15)$$

For convenience of expression, we set:

$$J(y) = C_5 - C_6 - R_6 + R_7 - B \cdot \beta \cdot y -$$
$$C_7 \cdot \beta \cdot y + K \cdot \beta \cdot y + R_8 \cdot \beta \cdot y +$$
$$B \cdot \theta \cdot y + C_7 \cdot \theta \cdot y - K \cdot \theta \cdot y -$$
$$R_8 \cdot \theta \cdot y - R_8 \cdot \beta \cdot x \cdot y - B \cdot \theta \cdot x \cdot y -$$
$$C_7 \cdot \theta \cdot x \cdot y + K \cdot \theta \cdot x \cdot y + R_8 \cdot \theta \cdot x \cdot y +$$
$$B \cdot \beta \cdot x \cdot y + C_7 \cdot \beta \cdot x \cdot y - K \cdot \beta \cdot x \cdot y.$$

According to the stability theorem of differential equations, the probability for passengers to choose co-governance can be stable if $F(z) = 0$ and $F'(z) < 0$. As $J(y) = 0$, we can obtain:

$$y^* = \frac{C_6 - C_5 + R_6 - C_7}{(1-x) \cdot (\theta - \beta) \cdot (B - K + C_7 - R_8)}.$$

Proposition 3: when $y = y^*$, all z are constantly the evolutionary stability strategy; when $y > y^*$, $z = 0$ is the evolutionary stability strategy; and when $y < y^*$, $z = 1$ is the evolutionary stability strategy.

Proof 3: $J(y)$ is an increasing function according to $J'(y) < 0$. When $y = y^*$, $J(y) = 0$, $F(z) = 0$ and $F'(z) = 0$, all z are under a stable state in this case; when $y > y^*$, $J(y) < 0$, $F'(z) < 0$, $1 - 2 \cdot z > 0$, $z < 0.5$, and $z = 0$ constitute the evolutionary stability strategy under this circumstance; and when $y < y^*$, $J(y) > 0$, $F'(z) < 0$, $1 - 2 \cdot z < 0$, $z > 0.5$, and $z > 0.5$ constitute the evolutionary stability strategy in this case.

Proposition 3 indicates that when the probability of passengers choosing to participate in co-governance is y^*, online car-hailing platforms maintain the initial strategy; when this probability is greater than y^*, online car-hailing platforms choose the strategy of weak supervision; and when the probability is less than y^*, online car-hailing platforms select the strategy of strong supervision.

3.4.4. Analysis of the system equilibrium strategy

To further analyse the system stability and equilibrium strategy, $F(x) = F(y) = F(z) = 0$ is set to solve the local equilibrium points of the system in combination with the above replicator dynamics equations, i.e., $X_1 = (0, 0, 0)$, $X_2 = (1, 0, 0)$, $X_3 = (0, 1, 0)$, $X_4 = (0, 0, 1)$, $X_5 = (1, 1, 0)$, $X_6 = (1, 0, 1)$, $X_7 = (0, 1, 1)$ and $X_8 = (1, 1, 1)$. Combining Freidman's method to judge the equilibrium strategy of the evolutionary game, the Jacobian matrix of this game system is solved as follows.

The above equilibrium points are substituted into this Jacobian matrix to solve the corresponding eigenvalues, as shown in Table 3.

$$A = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix};$$

$$\frac{\partial F(x)}{\partial x} = -x \cdot \big(C_2 - C_1 + R_1 - R_2 + R_3 + R_4 \cdot y -$$
$$R_3 \cdot z + K \cdot \beta \cdot y + R_3 \cdot y \cdot z + K \cdot \theta \cdot y \cdot z - K \cdot \beta \cdot y \cdot z\big) -$$
$$(x-1) \cdot \big(C_2 - C_1 + R_1 - R_2 + R_3 + R_4 \cdot y - R_3 \cdot z +$$
$$K \cdot \beta \cdot y + R_3 \cdot y \cdot z + K \cdot \theta y \cdot z - K \cdot \beta \cdot y \cdot z\big);$$

$$\frac{\partial F(x)}{\partial y} = -x \cdot (x-1) \cdot \big(R_4 +$$
$$K \cdot \beta + R_3 \cdot z - K \cdot \beta \cdot z + K \cdot \theta \cdot z\big);$$

$$\frac{\partial F(x)}{\partial z} = x \cdot (x-1) \cdot \big(R_3 -$$
$$R_3 \cdot y + K \cdot \beta \cdot y - K \cdot \theta \cdot y\big);$$

$$\frac{\partial F(y)}{\partial x} = y \cdot (y-1) \cdot \big(B \cdot \beta - B \cdot \beta \cdot z + B \cdot \theta \cdot z\big);$$

$$\frac{\partial F(y)}{\partial y} = (y-1) \cdot \big(C_4 - D - B \cdot \beta + B \cdot \beta \cdot x +$$
$$B \cdot \beta \cdot z - B \cdot \theta \cdot z + B \cdot \theta \cdot x \cdot z - B \cdot \beta \cdot x \cdot z\big) +$$
$$y \cdot \big(C_4 - D - B \cdot \beta + B \cdot \beta \cdot x + B \cdot \beta \cdot z -$$
$$B \cdot \theta \cdot z + B \cdot \theta \cdot x \cdot z - B \cdot \beta \cdot x \cdot z\big);$$

$$\frac{\partial F(y)}{\partial z} = y \cdot (y-1) \cdot \big(B \cdot \beta - B \cdot \theta - B \cdot \beta \cdot x + B \cdot \theta \cdot x\big);$$

$$\frac{\partial F(z)}{\partial x} = z \cdot (z-1) \cdot \big(B \cdot \beta \cdot y + C_7 \cdot \beta \cdot y - K \cdot \beta \cdot y -$$

Table 3. Stability analysis of equilibrium points

Equilibrium point	Eigenvalue λ	Stability condition
$X_1=(0,0,0)$	$\lambda_1=C_2-C_1+R_1-R_2+R_3$; $\lambda_2=D-C_4+B\cdot\beta>0$; $\lambda_3=C_6-C_5+R_6-R_7$	saddle point or unstable point
$X_2=(1,0,0)$	$\lambda_1=C_1-C_2-R_1+R_2-R_3$; $\lambda_2=D-C_4>0$; $\lambda_3=C_6-C_5+R_6-R_7$	saddle point or unstable point
$X_3=(0,1,0)$	$\lambda_1=C_2-C_1+R_1-R_2+R_3+R_4+K\cdot\beta$; $\lambda_2=C_4-D-B\cdot\beta<0$; $\lambda_3=C_6-C_5+R_6-R_7+(B+C_7-K-R_8)\cdot\beta+(K+R_8-B-C_7)\cdot\theta$	when $C_2-C_1+R_1-R_2+R_3+R_4+K\cdot\beta<0$ and $C_6-C_5+R_6-R_7+(B+C_7-K-R_8)\cdot\beta+(R_8+K-B-C_7)\cdot\theta<0$, the system can reach Evolutionarily Stable State (ESS)
$X_4=(0,0,1)$	$\lambda_1=C_2-C_1+R_1-R_2$; $\lambda_2=D-C_4+B\cdot\theta>0$; $\lambda_3=C_5-C_6-R_6+R_7$	saddle point or unstable point
$X_5=(1,1,0)$	$\lambda_1=C_1-C_2-R_1+R_2-R_3-R_4-K\cdot\beta$; $\lambda_2=C_4-D<0$; $\lambda_3=C_6-C_5+R_6-R_7$	when $C_1-C_2-R_1+R_2-R_3-R_4-K\cdot\beta<0$ and $C_6-C_5+R_6-R_7<0$, the system can reach ESS
$X_6=(1,0,1)$	$\lambda_1=C_1-C_2-R_1+R_2$; $\lambda_2=D-C_4>0$; $\lambda_3=C_5-C_6-R_6+R_7$	saddle point or unstable point
$X_7=(0,1,1)$	$\lambda_1=C_2-C_1+R_1-R_2+R_3+R_4+K\cdot\theta$; $\lambda_2=C_4-D-B\cdot\theta<0$; $\lambda_3=C_5-C_6-R_6+R_7+(B+C_7-K-R_8)\cdot\theta+(K+R_8-B-C_7)\cdot\beta$	when $C_2-C_1+R_1-R_2+R_3+R_4+K\cdot\theta<0$ and $C_5-C_6-R_6+R_7+(B+C_7-K-R_8)\cdot\theta+(K+R_8-B-C_7)\cdot\beta<0$, the system can reach ESS
$X_8=(1,1,1)$	$\lambda_1=C_1-C2-R_1+R_2-R_3-R_4-K\cdot\theta$; $\lambda_2=C_4-D<0$; $\lambda_3=C_5-C_6-R_6+R_7$	when $C_1-C_2-R_1+R_2-R_3-R_4-K\cdot\theta<0$ and $C_5-C_6-R_6+R_7<0$, the system can reach ESS

$$R_8\cdot\beta\cdot y-B\cdot\theta\cdot y-C_7\cdot\theta\cdot y+K\cdot\theta\cdot y+R_8\cdot\theta\cdot y);$$

$$\frac{\partial F(z)}{\partial y}=-z\cdot(z-1)\cdot(B\cdot\beta+C_7\cdot\beta-K\cdot\beta- R_8\cdot\beta-B\cdot\theta-C_7\cdot\theta+K\cdot\theta+R_8\cdot\theta- B\cdot\beta\cdot x-C_7\cdot\beta\cdot x+K\cdot\beta\cdot x+R_8\cdot\beta\cdot x+ B\cdot\theta\cdot x+C_7\cdot\theta\cdot x-K\cdot\theta\cdot x-R_8\cdot\theta\cdot x);$$

$$\frac{\partial F(z)}{\partial z}=(z-1)\cdot(C_5-C_6-R_6+R_7-B\cdot\beta\cdot y- C_7\cdot\beta\cdot y+K\cdot\beta\cdot y+R_8\cdot\beta\cdot y+B\cdot\theta\cdot y+ C_7\cdot\theta\cdot y-K\cdot\theta\cdot y-R_8\cdot\theta\cdot y-R_8\cdot\beta\cdot x\cdot y- B\cdot\theta\cdot x\cdot y-C_7\cdot\theta\cdot x\cdot y+K\cdot\theta\cdot x\cdot y+ R_8\cdot\theta\cdot x\cdot y+B\cdot\beta\cdot x\cdot y+C_7\cdot\beta\cdot x\cdot y- K\cdot\beta\cdot x\cdot y)+z\cdot(C_5-C_6-R_6+R_7- B\cdot\beta\cdot y-C_7\cdot\beta\cdot y+K\cdot\beta\cdot y+R_8\cdot\beta\cdot y+ B\cdot\theta\cdot y+C_7\cdot\theta\cdot y-K\cdot\theta\cdot y-R_8\cdot\theta\cdot y- R_8\cdot\beta\cdot x\cdot y-B\cdot\theta\cdot x\cdot y-C_7\cdot\theta\cdot x\cdot y+ K\cdot\theta\cdot x\cdot y+R_8\cdot\theta\cdot x\cdot y+B\cdot\beta\cdot x\cdot y+ C_7\cdot\beta\cdot x\cdot y-K\cdot\beta\cdot x\cdot y).$$

According to Lyapunov's 1st theory (indirect method), if all 3 eigenvalues are negative, the equilibrium point is an evolutionary stability point. If all 3 eigenvalues are positive, the point is unstable. When 1 or 2 eigenvalues are positive, the point is a saddle point. Table 3 shows the stability of each equilibrium point. As shown in Table 3, none of the equilibrium points $X_1=(0,0,0)$, $X_2=(1,0,0)$, $X_4=(0,0,1)$ and $X_6=(1,0,1)$ meet the stability criteria according to the Lyapunov method (indirect process), indicating that they are unstable points and do not represent evolutionary stability strategies. However, equilibrium points $X_1=(0,0,0)$ can achieve evolutionary stability by satisfying the asymptotic stability conditions, making the corresponding strategies evolutionary stability strategies. The changes in these evolutionary stability strategies are further analysed and discussed below.

Scenario I: Convergence to the evolutionary game equilibrium point $X_3=(0,1,0)$: when $R_1-R_2+R_3+R_4+K\cdot\beta<C_1-C_2$ and $(\theta-\beta)\cdot(K-B+R_8-C_7)+R_6-R_7<C_5-C_6$, $X_3=(0,1,0)$ is the stability point of the system's strategy evolution. The corresponding strategy is as follows: online car-hailing drivers choose illegal operation, passengers choose to participate in co-governance, and online car-hailing platforms lean toward weak supervision.

Scenario II: Convergence to the evolutionary game equilibrium point $X_5 = (1,1,0)$: when $R_2 - R_1 - R_3 - R_4 - K \cdot \beta < C_2 - C_1$ and $C_6 - C_5 < R_7 - R_6$, $X_5 = (1,1,0)$ is the stability point of the system's strategy evolution. The corresponding strategies are as follows: online car-hailing drivers prefer compliance operations, passengers choose to participate in co-governance, and online car-hailing platforms select weak supervision.

Scenario III: Convergence to the evolutionary game equilibrium point $X_7 = (0,1,1)$: when $R_1 - R_2 + R_3 + R_4 + K \cdot \theta < C_1 - C_2$ and $(\theta - \beta) \cdot (B - K + C_7 - R_8) + R_7 - R_6 < C_6 - C_5$, $X_7 = (0,1,1)$ is the stability point of the system's strategy evolution. The corresponding strategy is as follows: online car-hailing drivers choose illegal operation, passengers choose to participate in co-governance, and online car-hailing platforms lean toward strong supervision.

Scenario IV: Convergence to the evolutionary game equilibrium point $X_8 = (1,1,1)$: when $R_2 - R_1 - R_3 - R_4 - K \cdot \theta < C_2 - C_1$ and $C_5 - C_6 < R_6 - R_7$, $X_8 = (1,1,1)$ is the stability point of the system's strategy evolution. The corresponding strategy is as follows: online car-hailing drivers select compliance operations, passengers choose to participate in co-governance, and online car-hailing platforms prefer strong supervision.

4. Simulation analysis

The stability analysis of the equilibrium points indicates that the game system may support evolutionary stability strategies. This study primarily investigates the evolution mechanism of the equilibrium point $(1,1,1)$. Specifically, the ideal stable state for the system is defined as (participation in co-governance evaluation, compliance operation, strong supervision). Numerical simulation analysis was conducted via MATLAB 2019b (*https://www.mathworks.com*) to examine how relevant factors influence each participant's strategies and behaviours, promoting the system's convergence to this ideal stable state. On the basis of the current economic context of the online car-hailing industry, the multi-stakeholder strategy game for online car-hailing operations was analysed with $(1,1,1)$ as the foundational equilibrium point. Parameter values were derived primarily from literature (Wang *et al.* 2023) as well as industry data, including the *2024 Automotive Industry Research Report* (Sun 2024) and the report on *Analysis of the Current Development Status and Investment Prospects of China's Ride-Hailing Industry* (*2024–2031*) (GRN 2024). The final assigned parameter values are presented in Table 4.

Data selection principles: 1st, as a representative city of China's ride-hailing market, Guangzhou features a large market size, fierce competition, and strict government regulation of the ride-hailing industry. Shenzhen, another significant ride-hailing market, provides important reference data for parameter assignment through its market operation monitoring. According to Guangzhou's June 2024 monitoring data (Sun 2024), the average daily revenue per ride-hailing vehicle was 386.18 ¥. Based on industry averages and data from other cities, the net revenue per trip for ride-hailing drivers is estimated at 25 ¥. If drivers gain extra income through violations (e.g., taking detours, not using the meter), their revenue per trip from non-compliant operations is set at 45 ¥. Also, drawing on the proportion of "poor service attitude" complaints in Guangzhou's ride-hailing passenger complaints concluded by the transportation authorities, compliant drivers receive reputation benefits of 10 ¥ from the platform. Combining data from Guangzhou's transportation law enforcement on ride-hailing violations, non-compliant drivers suffer reputation losses of 20 ¥ from passenger negative reviews and platform penalties. Passenger satisfaction surveys indicate that the convenience and comfort of ride-hailing services bring passengers a benefit of 50 ¥. In combination with Guangzhou's average ride-hailing service charges, the average cost for passengers using ride-hailing services is set at 40 ¥. 2nd, while the ride-hailing industry is developing rapidly, it faces many challenges, such as driver non-compliance, passenger rights protection, and platform regulation. Therefore, this study sets the initial probability of drivers choosing "compliant operations" at 0.5, the initial probability of passengers choosing "participation in co-governance" at 0.5, and the initial probability of the platform choosing "strict regulation" at 0.5. Finally, combining the results of equilibrium analysis and based on the principle of equation balance, specific parameter values are assigned. Using evolutionary game theory, the study explores how changes in key parameter values affect evolutionary equilibrium results. Under conditions that meet the parameter value range requirements, key parameter values are assigned for simulation analysis.

Table 4. Value assignment to simulation parameters

Parameter	R_1	R_2	C_1	C_2	R_3	R_4	K
Value	25	45	15	10	10	20	100
Parameter	R_5	C_3	D	C_4	S	B	R_6
Value	50	40	15	5	40	20	20
Parameter	C_5	R_7	C_6	R_8	C_7	θ	β
Value	10	10	5	50	30	0.9	0.1

4.1. Initial evolution path

The simulation results confirmed the accuracy of the theoretical calculations, demonstrating that, given the assigned values for the constraint conditions, the tripartite evolution endpoint consistently reached $(1,1,1)$ regardless of the initial value changes. Drivers opt for compliant operations, passengers choose to participate in co-governance, and ride-hailing platforms select stringent regulation. Additionally, the initial strategy affects the rate at which each of the 3 game participants evolves their willingness. The higher the initial probability is, the faster the convergence rate, as illustrated in Figure 2.

4.2. Influence of investigation and the treatment rate on the evolution path under strong supervision of online car-hailing platforms

With the other parameters unchanged, the values of $\theta = 0.9$, $\theta = 0.8$ and $\theta = 0.7$ were set, and the resulting 3D evolution paths are shown in Figure 3. The simulation results indicate that as the investigation and treatment rates increase, the convergence to the stable equilibrium point $(1, 1, 1)$ accelerates. However, as shown in Figure 4, under conditions of strong supervision, online car drivers are more inclined toward compliance with higher investigation and treatment rates.

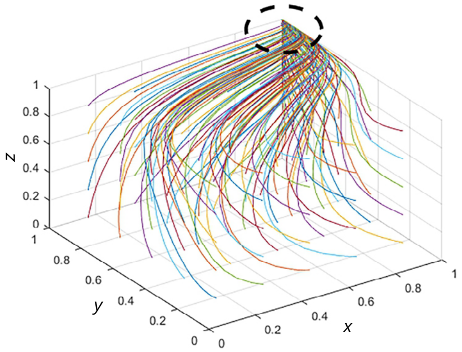

Figure 2. Initial evolution path diagram

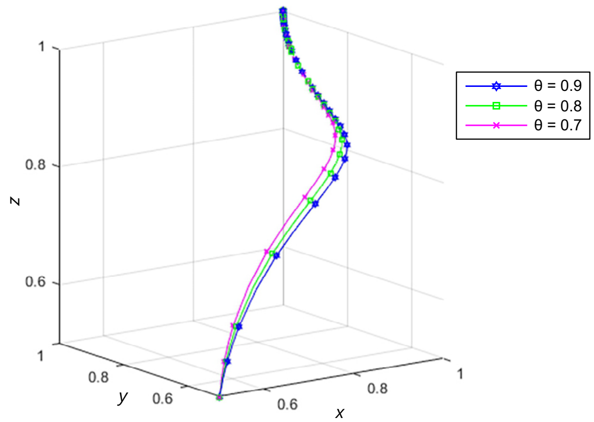

Figure 3. 3D evolution path diagram of changes in the investigation and treatment rates θ

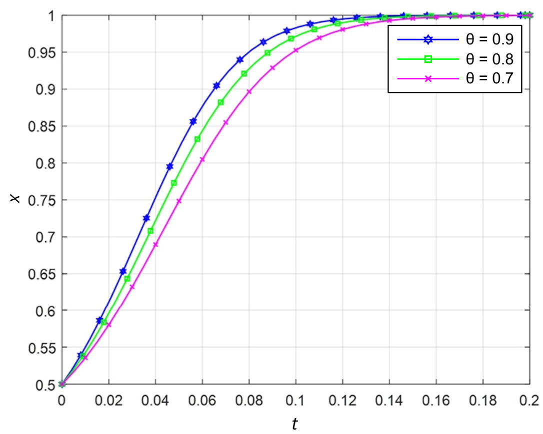

Figure 4. 2D diagram of the influence of the investigation and treatment rate θ on online car drivers

A high investigation and treatment rate under strong supervision significantly promotes compliance among online car drivers. This result stems from 2 main factors: 1st, the high rate of investigation and treatment amplifies the penalties for violations, increasing the economic costs of noncompliance and encouraging drivers to avoid infractions; 2nd, frequent investigations reinforce industry standards, helping drivers recognize that rule adherence is fundamental not only to personal ethics but also to maintaining industry order and enhancing service quality. This heightened awareness further motivates drivers to follow industry norms, leading to continuous improvement in the overall quality of online car-hailing services and establishing a positive feedback mechanism.

The research findings indicate that intensified regulatory efforts significantly enhance the compliance of ride-hailing drivers. Higher rates of enforcement not only expedite the attainment of market equilibrium but also motivate drivers to adhere to regulations by increasing the costs associated with non-compliance and reinforcing awareness of industry standards, thereby promoting an overall improvement in service quality.

4.3. Influence of investigation and the treatment rate on the evolution path under weak supervision of online car-hailing platforms

With other parameters unchanged, values of $\beta = 0.1$, $\beta = 0.2$ and $\beta = 0.3$ were set, and the 3D evolution paths are displayed in Figure 5. The results indicate that once the investigation and treatment rates reach a certain threshold, convergence to the stable equilibrium point $(1, 1, 1)$ occurs more rapidly. As shown in Figure 6, drivers' strategies are initially less influenced by the investigation and treatment rates. However, under strong supervision, a higher investigation and treatment rate consistently increase drivers' tendency toward compliance.

A high investigation and treatment rate, even under weak supervision, also positively affects drivers' compliance. The simulation results show that, despite a less stringent regulatory environment, increasing the intensity of investigations and treatments can meaningfully alter drivers' behaviour. This approach communicates a clear message to drivers: tolerance for illegal operations is diminishing, prompting them to adjust their practices to align with market rules and regulatory requirements.

In general, regardless of the regulatory strategy employed by online car-hailing platforms, increasing the investigation and treatment rates creates a strong incentive for drivers to comply. Since drivers depend on these platforms for their livelihood, they are highly responsive to factors affecting their income, including penalties for noncompliance. A high investigation and treatment rate increases the direct cost of illegal behaviours, encouraging drivers to swiftly adapt their actions to avoid potential financial losses.

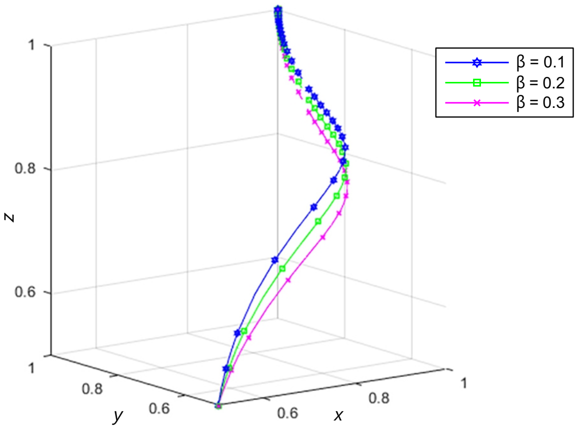

Figure 5. 3D evolution path diagram of changes in the investigation and treatment rates β

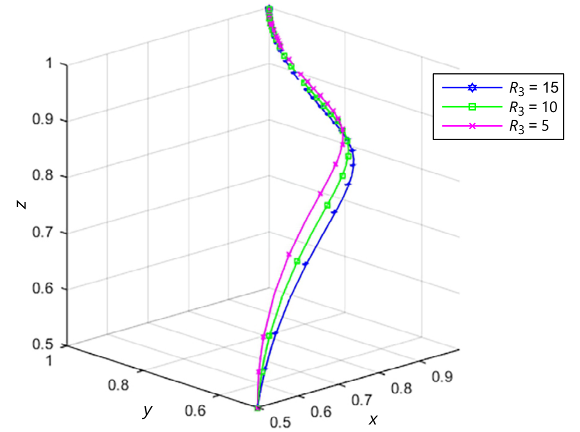

Figure 7. 3D evolution path diagram of changes in drivers' positive reputation revenue R_3

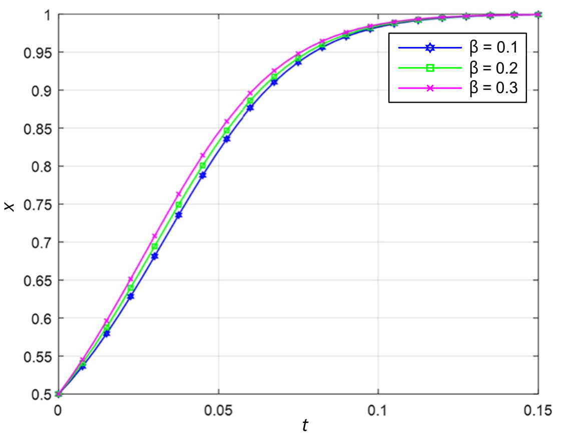

Figure 6. 2D diagram of the influence of the investigation and treatment rates on online car drivers

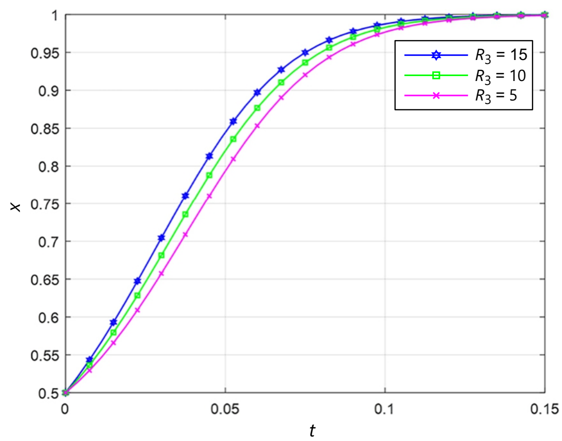

Figure 8. 2D diagram of the influence of changes in drivers' positive reputation revenue R_3 on online car drivers

4.4. Influence of drivers' positive reputation revenue on the evolution path

With other parameters unchanged, drivers' positive reputation revenue was set to $R_3 = 15$, $R_3 = 10$ and $R_3 = 5$, and the resulting 3D evolution paths are shown in Figure 7. The simulation results indicate that although changes in drivers' positive reputation revenue do not affect the system's evolutionary outcome, they do influence the rate of evolution. As shown in Figure 8, as drivers' positive reputation revenue increases, x converges to 1, and drivers' decisions evolve toward compliance.

When online car-hailing drivers receive positive reputation revenue for compliance, this provides a strong incentive for choosing compliant strategies. Since compliance increases drivers' revenue, they are naturally inclined to adopt compliant practices to maximize their own interests.

The research findings reveal that while the positive reputational gains of drivers do not directly influence the evolutionary outcomes, they significantly affect the rate of evolution. As depicted in Figures 7 and 8, an increase in drivers' positive reputational benefits leads to a more rapid convergence towards compliant operational strategies, indicating that these gains provide a positive incentive for drivers to opt for compliant practices.

4.5. Influence of drivers' negative reputation loss on the evolution path

With other parameters unchanged, drivers' negative reputation loss from illegal operation was set to $R_4 = 25$, $R_4 = 20$ and $R_4 = 15$, and the resulting 3D evolution paths are shown in Figure 9. The simulation results indicate that although changes in drivers' negative reputation loss do not alter the system's evolutionary outcome, they do affect the rate of evolution, accelerating convergence to the equilibrium stability point $(1,1,1)$. As shown in Figure 10, drivers' negative reputation loss encourages them to adopt compliant strategies, as bounded rationality leads drivers to recognize that illegal actions reduce their revenue, thus incentivizing them to choose compliance.

The research outcomes demonstrate that although drivers' negative reputational losses do not alter the ultimate stability of evolution, they significantly influence the rate at which this stability is achieved. As shown in Figures 9 and 10, the evolutionary process hastens towards an equilibrium state with increased negative reputational losses for drivers, highlighting the positive role of such losses in encouraging drivers to adopt compliant operational strategies.

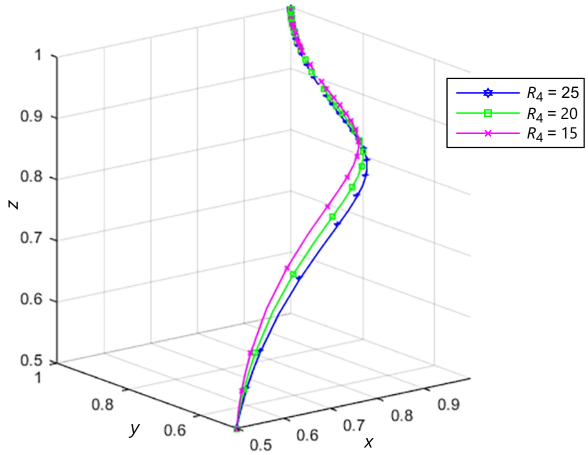

Figure 9. 3D evolution path diagram of changes in drivers' negative reputation loss R_4

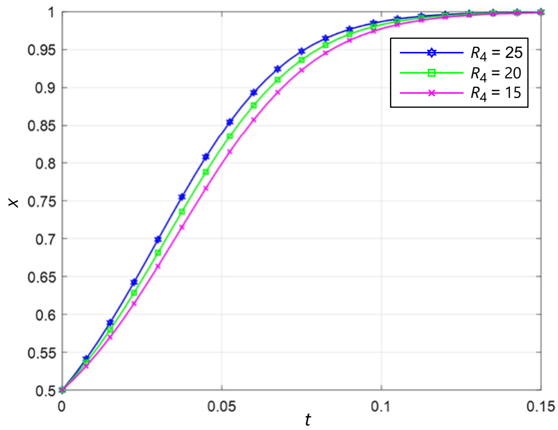

Figure 10. 2D diagram of the influence of changes in drivers' negative reputation loss R_4 on online car drivers

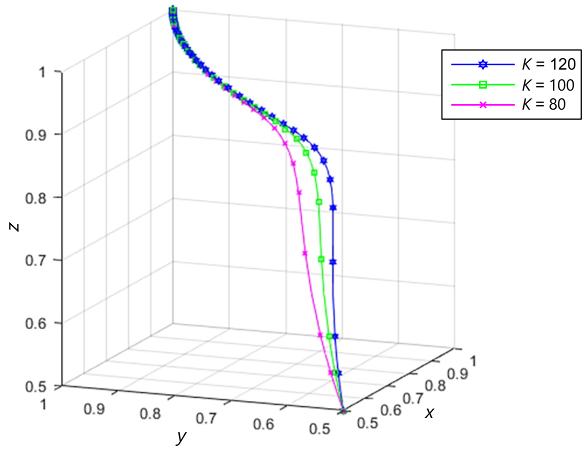

Figure 11. 3D evolution path diagram of changes in guarantee deposit K

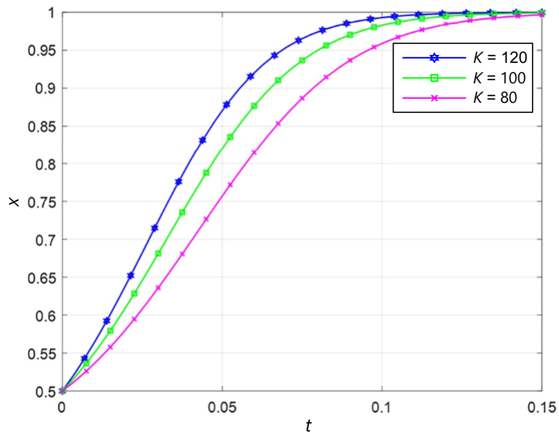

Figure 12. 2D diagram of the influence of changes in guarantee deposit K on online car drivers

4.6. Influence of guarantee deposits on the evolution path

With the other parameters unchanged, $K=120$, $K=100$ and $K=80$ were set, and the 3D evolution paths are displayed in Figure 11. The guarantee deposit imposed by online car-hailing platforms for drivers' illegal operations does not affect the final system result, which converges to the equilibrium stability point $(1,1,1)$, but it does impact the speed of strategy adjustments by both drivers and platforms. Figure 12 shows that as the guarantee deposit amount increases, x converges to 1 more quickly, indicating a faster shift toward compliance among drivers.

Similarly, Figure 13 shows that with higher guarantee deposits charged to drivers, z converges to 1, with the evolutionary paths overlapping in the later stages, suggesting that online car-hailing platforms evolve toward stronger supervision. This occurs because as the deposit increases, so does the cost of illegal actions for drivers. Stronger enforcement by platforms enhances revenue potential, making compliance more attractive for drivers and strong supervision more favourable for platforms.

The research findings indicate that the level of deposit imposed by ride-hailing platforms on drivers for non-compliant operations does not alter the evolutionary outcome but significantly influences the rate at which equilibrium is achieved. As depicted in Figures 12 and 13, an increase in the deposit amount leads to a quicker convergence towards compliance for drivers and towards stringent regulation for platforms. This trend suggests that higher financial penalties for non-compliance raise the cost of such

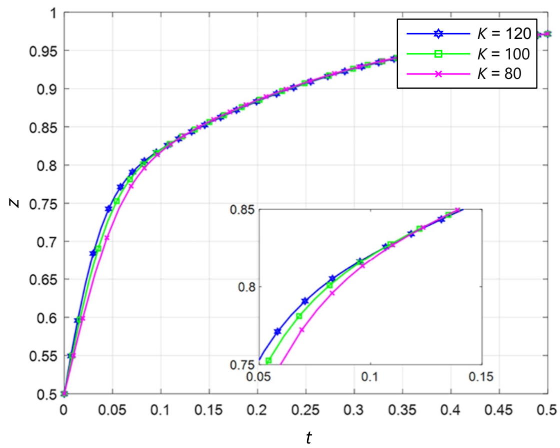

Figure 13. 2D diagram of the influence of changes in guarantee deposits K on online car-hailing platforms

behaviour for drivers, thereby incentivizing them to adhere to regulations, and simultaneously encourage platforms to adopt stronger regulatory measures due to increased enforcement benefits.

4.7. Influence of platforms' promotion rewards on the evolutionary path

With the other parameters unchanged, $D=20$, $D=15$, and $D=10$ are set, and the simulation results of the 3D evolution paths are shown in Figure 14. Variations in platform promotion rewards do not alter the final system result, which converges to the equilibrium stability point $(1,1,1)$. Figure 15 indicates that as passenger rewards increase, y converges to 1 at a faster rate, with passengers being more likely to adopt co-governance behaviours. As shown in Figure 16, higher platform promotion rewards slightly accelerate the rate at which platforms adopt strong supervision strategies, although the effect is minimal.

This minor impact occurs because supervision strategies are often guided by long-term planning and strategic goals rather than short-term changes in reward incentives. If passengers receive platform rewards, it encourages co-governance participation while somewhat diminishing the platform's inclination toward strong supervision. Increased passenger rewards increase the revenue from co-governance, incentivizing participation but also increase platform costs. Thus, passenger participation in co-governance accelerates, whereas the platform's shift toward strong supervision slows slightly.

The research findings indicate that while the promotional rewards offered by the platform do not significantly affect the final outcome of the evolution, they have a substantial impact on the speed of reaching equilibrium. Figures 14–16 demonstrate that as the level of promotional rewards increases, the rate of evolution towards cooperative governance among passengers accelerates, whereas the evolution towards stringent regulatory strategies by the platform slows down relatively. This suggests that promotional rewards primarily function by incentivizing passenger participation in cooperative governance, with a lesser immediate effect on the platform's regulatory strategies, reflecting the long-term and strategic considerations inherent in the platform's regulatory decision-making.

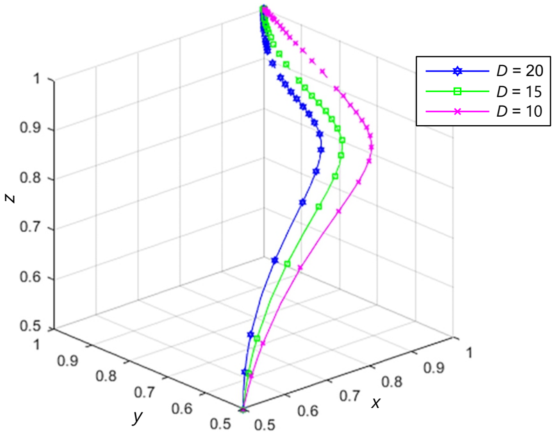

Figure 14. 3D evolution path diagram of changes in platforms' promotion reward *D*

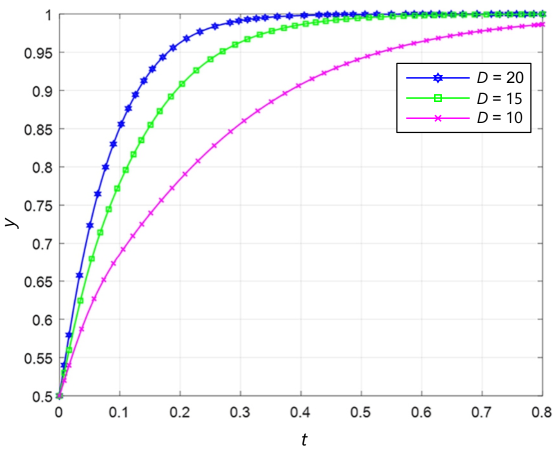

Figure 15. 2D diagram of the influence of changes in platform promotion rewards *D* on passengers

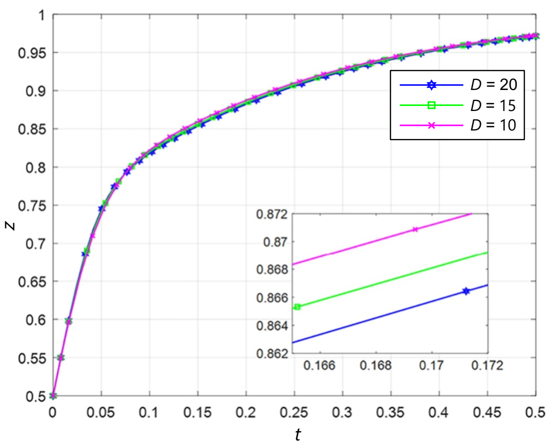

Figure 16. 2D diagram of the influence of changes in platform promotion rewards on online car-hailing platforms

4.8. Influence of compensation B on the evolution path

With the other parameters unchanged and $B=10$ set, the 3D evolution paths are shown in Figure 17. The increase in passenger compensation by online car-hailing platforms does not change the system's final result, which converges to the equilibrium stability point $(1,1,1)$, but it does influence the rate of convergence. As shown in Figure 18, higher compensation leads y to converge to 1 more quickly, with passengers increasingly adopting co-governance behaviours.

However, Figure 19 indicates that as passenger compensation decreases, z also converges to 1 faster, indicating that platform strategies shift toward strong supervision. Increased compensation positively encourages passenger participation in co-governance while placing negative pressure on platforms' strong supervision tendencies. This is because higher compensation increases passengers' incentives to participate in co-governance evaluations while simultaneously increasing platform costs. Thus, the rate at which passengers shift toward co-governance accelerates, whereas the platform's move toward strong supervision slows slightly.

The research findings indicate that while the compensation level offered by ride-hailing platforms to passengers does not impact the ultimate stability of evolution, it significantly affects the rate of evolution. As shown in Figures 17–19, an increase in the compensation level accelerates the strategy evolution towards cooperative governance among passengers, while the evolution towards stringent regulatory strategies by the platform slows down relatively. This reflects that enhancing compensation for passengers can effectively motivate their participation in co-governance, but may lead platforms to more cautiously consider stringent regulatory strategies in the short term, as increased compensation could elevate the operational costs of the platform.

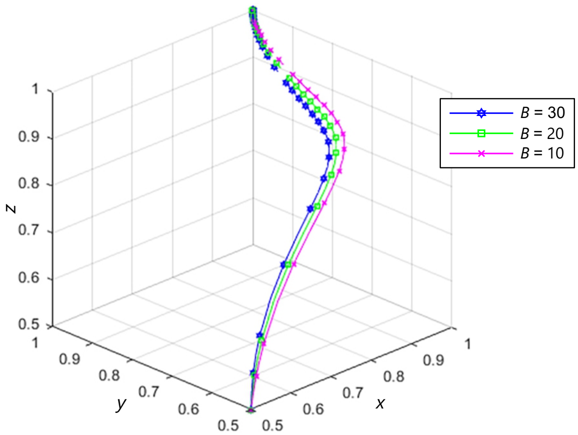

Figure 17. 3D evolution path diagram of changes in compensation *B*

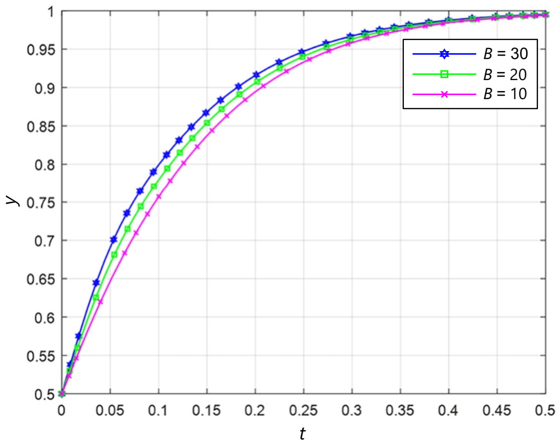

Figure 18. 2D diagram of the influence of changes in compensation *B* on passengers

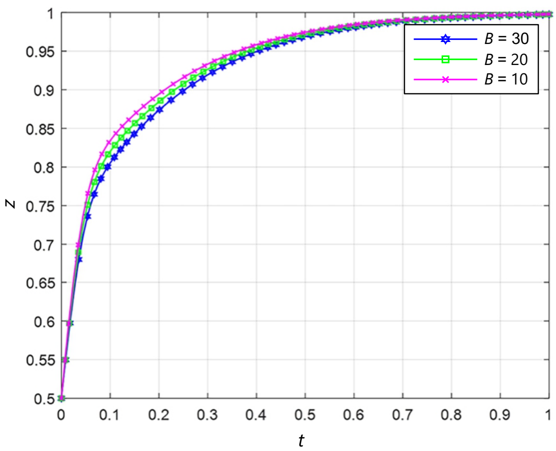

Figure 19. 2D diagram of the influence of changes in compensation *B* on online car-hailing platforms

4.9. Influence of social reputation revenue on the evolution path

With other parameters unchanged, social reputation revenue was set to $R_8 = 60$, $R_8 = 50$ and $R_8 = 40$, and the 3D evolution paths are displayed in Figure 20. The social reputation revenue earned by online car-hailing platforms does not affect the final system stability, which converges to the equilibrium stability point $(1,1,1)$, but it does impact the evolution rate. Figure 21 shows that increased social reputation revenue positively incentivizes platforms to adopt a strong supervision strategy. This effect occurs because a good social reputation allows platforms to achieve more stable and sustained revenue over time.

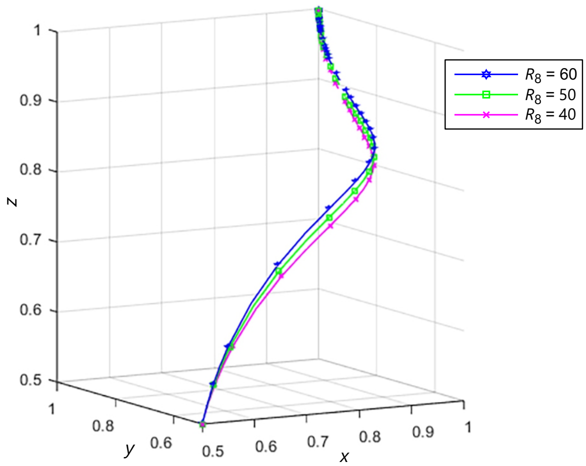

Figure 20. 3D evolution path diagram of changes in social reputation revenue R_8

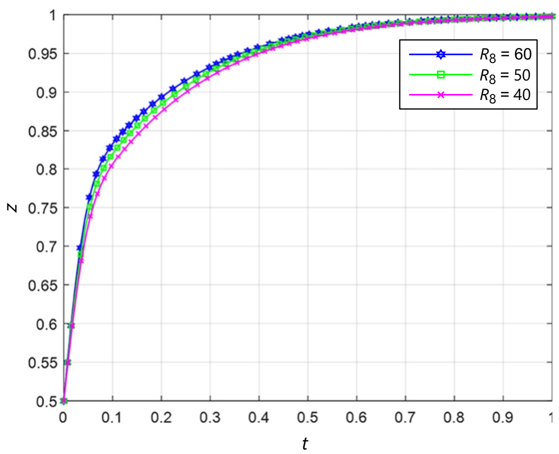

Figure 21. 2D diagram of the influence of changes in social reputation revenue R_8 on online car-hailing platforms

The research findings indicate that although the social reputational gains acquired by ride-hailing platforms do not affect the ultimate stability of their evolutionary outcomes, they do indeed influence the rate of evolution. Figures 20 and 21 reveal that as the platforms' social reputational benefits increase, the propensity for platforms to opt for stringent regulatory strategies is enhanced, and this propensity accelerates with higher benefits. This suggests that heightened social reputational gains can positively motivate platforms to implement more rigorous regulatory measures, potentially fostering the healthy development of the entire ride-hailing industry.

5. Discussion

To address the issue of illegal operations by online car drivers and platform supervision in the online car-hailing industry, a tripartite evolutionary game model involving passengers, drivers, and online car-hailing platforms was developed. This model analyses each participant's strategy selection within the operational chain of online car-hailing, as well as the interaction mechanisms at play. This study reveals the dynamic evolution of strategies among passengers, drivers, and platforms, along with factors influencing different strategy selection modes. Model analysis and simulation results indicate that effective supervision of the online car-hailing industry requires multi-stakeholder engagement, providing a new perspective for managing drivers' illegal behaviours:

- from the perspective of a tripartite evolutionary game involving drivers, passengers, and platforms, this study simultaneously considers how 2 critical stakeholders – platforms and passengers – influence drivers' decisions regarding illegal operations. The findings suggest that stronger platform supervision and greater passenger involvement in co-governance can effectively curb illegal behaviour among drivers. Unlike the literature, this study highlights the role of passenger participation in co-governance, offering a fresh research angle and underscoring the importance of multi-stakeholder involvement. A stability analysis of equilibrium points (Table 3) demonstrated that online car-hailing platforms can reduce driver misconduct by intensifying oversight, increasing guarantee deposits, and incentivizing compliance through passenger compensation. Higher passenger compensation fosters co-governance participation, which supports industry development, whereas lower compensation may increase platforms' supervision costs, leading them to favour strong supervision. Similarly, larger platform promotion rewards encourage passenger co-governance, although the impact on platforms' decisions is minimal. A nuanced observation is that reduced promotion rewards make platforms more inclined to adopt strong supervision. For drivers, positive reputation gains and negative reputation losses increase their inclination toward compliance, whereas platforms' social reputation revenues encourage a preference for strong supervision;
- the simulation analysis further illustrates that drivers' and platforms' strategy choices are influenced by various factors. As shown in the sensitivity analysis of parameters (Figures 2–21), all parties are more likely to adopt positive supervision and participate in co-governance when platforms intensify investigations, raise guarantee deposits, increase passenger compensation, and offer greater promotion rewards. These findings provide targeted strategies for platforms to increase the efficiency and effectiveness of supervision. Although previous studies have shown that platform enforcement intensity affects drivers' behaviour (Wan *et al.* 2022; Sun *et al.* 2019; You, Zhang 2024), this study offers a more systematic and comprehensive analysis, particularly highlighting the combined effects of passenger co-governance participation and platform actions on driver behaviour – a perspective rarely addressed in the literature;
- this study delves into the practical challenges encountered in the regulation of the ride-hailing market and the corresponding strategies to address these issues. In reality, the regulation of the ride-hailing market is confronted with a host of thorny problems, such as the high difficulty of law enforcement, the exorbitant compliance costs for platforms, and the limited participation of passengers. The existence of these problems severely restricts the improvement of regulatory effectiveness and makes it hard to achieve the desired state. To tackle the difficulties in law enforcement, the government and platforms should strengthen collaborative efforts. The government needs to provide clear regulatory guidance and technical support to platforms, which in turn should actively share operational data to enhance the efficiency and accuracy of law enforcement. In response to the issue of high compliance costs for platforms, the government can introduce tax incentives or subsidies to alleviate the economic burden on platforms. Meanwhile, platforms themselves should optimize operational processes and improve compliance management efficiency to reduce compliance costs. In addition, to break through the real-world limitations on passenger participation, platforms need to simplify the procedures for passenger participation in co-governance, optimize user experience design, lower the barriers to participation, and strengthen passenger education to raise awareness of the importance of co-governance and enhance their willingness and ability to participate. The implementation of these measures will not only help to enhance the effectiveness of regulation but also promote the healthy development of the ride-hailing industry. Through these discussions, this study offers a more comprehensive and in-depth perspective on addressing regulatory issues in the ride-hailing industry and provides valuable references for future research and practice.

6. Conclusions and implications

6.1. Main findings

To address the issue of illegal operations by drivers in the online car-hailing industry, a tripartite evolutionary game model involving online car-hailing platforms, drivers, and passengers was developed. This model examines the dynamic strategy selection processes of each party under various supervision modes, with simulations conducted to explore the factors influencing system equilibrium points. The main findings are as follows:

- ***strengthened supervision by platforms***: increased supervision of drivers' violations by online car-hailing platforms increases the likelihood of detecting and addressing illegal activities, which, in turn, increases the cost of noncompliance and lowers the incidence of violations. Additionally, higher guarantee deposits for drivers' illegal behaviours increase the financial penalties associated with violations, encouraging compliance. Drivers' decisions are also influenced by the combined effects of positive reputation gains and negative reputation losses, which jointly motivate compliance – positive reputation serves as an incentive, whereas negative reputation acts as a deterrent. By balancing these influences, drivers tend to choose compliance, as it maximizes their self-interest, supporting the sustainable development of the online car-hailing industry;
- ***passenger participation in co-governance***: passengers participate in co-governance primarily to receive compensation from online car-hailing platforms, increasing their revenue and stabilizing their preference for active participation. Higher compensation speeds up passengers' choice to participate in co-governance. Additionally, platforms' promotional rewards, such as discounts, points, or cash back, further encourage passenger engagement by increasing direct financial benefits and enthusiasm. In addition to providing material rewards, promotional incentives can also provide psychological benefits, such as a sense of achievement, belonging, or social identity, which further enhances passengers' willingness to participate in co-governance;
- ***interaction between social reputation and strong supervision***: there is a positive relationship between platforms' social reputation and strong supervision strategies. By aligning with regulatory standards, platforms can enhance their social standing and secure greater market opportunities. Over time, however, the impact of guarantee deposits on platforms' choice of strong supervision may vary with changing market conditions. Initially, a high guarantee deposit effectively prevents violations, reinforcing platforms' commitment to oversight. As time passes, however, stakeholders – including drivers, passengers, and platforms – may adapt to the guarantee deposit system, potentially reducing its deterrent effect. Drivers may find ways to circumvent high deposits, or platforms may identify alternative, more effective regulatory methods. Consequently, the role of guarantee deposits may evolve across different stages of platform supervision, with positive incentive effects fluctuating according to the market and regulatory environments.

6.2. Management implications

On the basis of the above research conclusions, the following recommendations are proposed to address governance challenges under online car-hailing platform supervision:

- ***establishing a stakeholder-driven supervision system***: online car-hailing platforms should promote joint supervision by the public and passengers by enhancing service quality oversight mechanisms and implementing transparent complaint feedback channels and public evaluation systems. Continuous driver training can also improve service quality and increase driver awareness of the supervision system. This multi-stakeholder co-governance approach fosters collective participation in oversight, improving both driver service quality and the effectiveness of platform regulatory measures. This approach builds public trust and lays the foundation for the industry's sustainable growth;
- ***leverage passenger supervision in online car-hailing***: incentivizing passengers who provide valuable feedback encourages broader participation in oversight. Passenger feedback can then support a rapid-response mechanism for addressing complaints and suggestions, ensuring timely problem resolution. Analysing common travel issues can also inform data-driven supervisory decisions. Additionally, in-app communication tools can facilitate direct passenger–driver interactions, helping to resolve misunderstandings and enhance service experiences. Passengers, as both service recipients and active participants, play crucial roles in improving service quality and fostering the healthy growth of the industry;
- ***expand supervision methods for drivers via diverse tools***: platforms should set clear service standards and codes of conduct, leverage big data and AI for real-time monitoring, and establish a fair, transparent driver evaluation system. Implementing a reward and penalty system on the basis of service quality can incentivize compliance, whereas effective feedback and appeal channels enable drivers to access evaluation results and lodge complaints if necessary. These strategies improve transparency throughout the supervision process and help build a comprehensive, effective oversight system that supports the standardized, sustainable development of the online car-hailing industry;
- ***tackling real-world regulatory challenges requires enhanced government-platform collaboration***: the government should offer platforms clear regulatory guidance and technological support, while platforms must actively share operational data to boost enforcement efficiency and accuracy. To ease platforms' compliance cost burden, the government can introduce tax incentives or subsidies. Platforms, in turn, should opti-

mize their operational processes and enhance the efficiency of compliance management to reduce costs. Furthermore, to overcome passenger participation barriers, platforms need to streamline co-governance procedures, refine user experience design, and lower participation thresholds. Strengthening passenger education to raise awareness of co-governance importance and boosting their participation willingness and ability is also crucial.

6.3. Limitations and perspectives

This study contributes valuable insights into the operational challenges of the online car-hailing industry; however, certain limitations remain, offering directions for future research and potential areas for extension. The limitations and anticipated future research goals are as follows:

- ***subjectivity of parameter setting***: despite efforts to align parameter selection with real-world conditions and incorporate insights from literature, some subjectivity remains in parameter choices within the evolutionary game model. Future research should aim to improve objectivity by employing more systematic data collection methods and quantitative analysis techniques for parameter optimization;
- ***comprehensiveness of sample coverage***: not all critical participants in the online car-hailing industry were fully represented in sample selection. To increase the universality and applicability of findings, future research should broaden the sample scope to include a wider variety of driver demographics, regional government policies, diverse platform operators, and other stakeholders. By addressing these areas, future research can provide a more accurate and comprehensive analysis, delivering deeper and more practical insights into the operational issues facing the online car-hailing industry.

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