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Research article

Evolutionary game analysis of carbon emission reduction in transportation infrastructure construction under dual regulation

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A B S T R A C T

Under the dual regulation of government intervention and environmental constraints, user demand, low-carbon awareness, and the willingness of construction enterprise to reduce carbon emissions are crucial to the realization of low-carbon transportation infrastructure construction. Basing on prospect theory, this paper constructs an evolutionary game model for the government, construction enterprise, and user, explores the stabilization of the three-game players' strategy choices, and discusses the influence of key parameters on the behavior evolution of relevant players through simulation analysis. The results indicate that: the regulatory cost when the government adopts incentives or no incentives is an important factor affecting the strategy choice. The enhancement of incentives by the government can promote the construction of enterprise and the selection of low-carbon transportation infrastructure by user. However, when the benefit of government credibility outweighs the incremental cost of household subsidies, carbon subsidies, and regulation, the government changes its strategy and no longer adopts encouraging strategy. Improving benefits of build low-carbon transportation infrastructure reducing incremental costs, setting a ladder carbon tax rate, increasing carbon tax rate for traditional construction, and decreasing for low-carbon construction is an effective approach to stimulate enterprise to construct low-carbon transportation infrastructure. The user's choice of low-carbon transportation infrastructure strategy is positively correlated with the subsidy received and is less affected by environmental benefits. And the construction enterprise's strategy choice hasn't been influenced by user, which is related to the public service characteristics of transportation infrastructure.

1. Introduction

With the swift progression of the global economy, the issue of global warming has garnered significant attention from the international community. Owing to the increased frequency of extreme weather disasters worldwide caused by greenhouse gas emissions, governments have actively advocated and implemented various carbon emission reduction measures [1]. China has established a "dual-carbon" goal of achieving carbon peak by 2030 and carbon neutrality by 2060 [2]. and has enacted a suite of carbon emission reduction policies, stringent carbon emission standards, and a carbon emission trading market to facilitate low-carbon and sustainable development, in response to the strategic imperative of resource conservation and emission reduction for achieving sustainable

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development [3].

To facilitate the promotion of green and low-carbon development in transportation infrastructure construction, targeted policies have been introduced by the state. In February 2021, the State Council issued the "Guiding Opinions on Accelerating the Establishment of a Sound Green, Low-carbon, and Circular Economic System," emphasizing the need to enhance the level of green development in transportation infrastructure (TI) by incorporating the concept of ecological and environmental protection throughout the entire process of TI planning, construction, operation, and maintenance [4]. On October 26, 2021, the State Council officially released the "Carbon Peak Action Plan by 2030," indicating that the transportation sector accounts for approximately 10 % of terminal carbon emissions. Considering the ongoing trend of urbanization and the improvement in living standards, it is crucial to strive for accelerating the formation of a green, low-carbon, and multi-modal transportation system [5]. In March 2023, the Ministry of Transportation and other five departments jointly issued the Five-Year Action Plan to Accelerate the Construction of a Strong Transportation State (2023–2027), stating that it will promote the construction of major transportation infrastructure projects, strive to build a modern and comprehensive transportation infrastructure system, and push forward the green and low-carbon transformation of transportation, and in order to accelerate the transformation of greening of the transportation infrastructure [6].In April 2024, the Ministry of Finance and the Ministry of Transportation issued the Notice on Supporting and Guiding the Digital Transformation and Upgrading of Highway and Waterway Transportation Infrastructure, pointing out that it will accelerate the digital transformation of transportation infrastructure, high side the traditional minimalist mode, focusing on the intensive and economical use, and prying the carrying capacity of transportation infrastructure to be significantly increased with less resource consumption [7].Although under the guidance of national strategic policies, the transportation industry has developed corresponding measures, proposing to promote the digital transformation of transportation, accelerate the construction of intelligent transportation, and facilitate the green and low-carbon transformation of the transportation sector. However, the realization of low-carbon transportation infrastructure construction and carbon emission reduction development, as well as the elimination of existing high-carbon development models, are still in the exploration stage [8]. As an essential component of infrastructure, transportation infrastructure contributes to increased carbon emissions during its construction and operation due to the extensive use of construction materials, among other factors. With the continuous enhancement of transportation infrastructure, regional markets and population density continue to expand, stimulating the increase of transportation activities and the consumption of significant amounts of fossil energy, exacerbating environmental pollution, and further escalating the challenges of carbon emissions control [9]. However, the current research on carbon emissions from transportation infrastructure primarily focuses on transportation-related carbon emissions, neglecting the impact of carbon emissions from transportation infrastructure construction [10]. Xie et al. [11] emphasized that the construction of transportation infrastructure is a crucial factor influencing urban carbon emissions. Technological progress in this field may potentially increase carbon emissions. Ming examined the impact of transportation infrastructure construction on haze pollution. He suggested that population density and economic growth are the main factors influencing CO_2 emissions from transportation infrastructure construction [12]. Churchill et al. [13] indicated that a 1 % increase in transportation infrastructure construction results in a 0.4 % increase in CO_2 emissions. Given the costly and time-consuming nature of transportation infrastructure construction, it poses a long-term impact that is challenging and expensive to modify [14]. Therefore, it is essential to expend research on reducing carbon emissions in transportation infrastructure construction, raise awareness among stakeholders regarding the emissions from transportation infrastructure construction, and facilitate the development of intelligent strategies to reduce carbon emissions.

The government can promote the reduction of carbon emission intensity by enterprises through administrative and economic means, and the implementation of government administrative interventions (carbon tax, emissions trading platform) has an impact on the technological and transportation structures of infrastructure projects [15]. The most effective way of government intervention policy is the carbon tax system, Wang et al. [16] and Duan et al. [17] examined the impact of carbon tax system on the strategic choice of carbon emission reduction behavior of enterprises, and concluded that a certain threshold of carbon tax rate is a necessary condition to promote energy saving and emission reduction, and appropriate carbon tax rate can accelerate the process of carbon emission reduction, and at the same time improve the environmental performance. Environmental regulation as an economic means for the government to regulate the low-carbon behavior of enterprises has a mandatory constraint. Liu et al. [18] analyzed the carbon reduction strategies of government and punish enterprise under environmental regulation, concluding that dynamic regulatory policies outperform static strategies. Stucki et al. [19] viewed environmental regulations as punitive measures and government intervention subsidies as incentives. However, some scholars hold opposing views, Giessen and Sahide [20] conducted an empirical analysis and found that environmental regulations result in increased costs and decreased competitiveness for enterprise, which is counterproductive to the emergence of corporate carbon emission reduction behavior. As observed from the preceding analysis, government intervention and environmental regulations have a significant impact on carbon emission reduction behavior. However, most relevant studies evaluate the impact of government intervention and environmental regulations on carbon emission reduction from a single perspective. In contrast, This study adopts a comprehensive approach, concurrently investigating decision-making choices and behavioral trends of carbon emission reduction by transportation infrastructure construction-related subjects under the dual constraints of government intervention (including, but not limited to, policies such as carbon taxes and subsidies) and environmental regulations (primarily concerning penalty mechanisms for environmental governance, such as various economic instruments).

The evolutionary game theory is a crucial method to analyze the behavioral strategy of carbon emission reduction for relevant parties. Sun et al. [21] considered different constraints and investigated the impact of carbon tax and subsidies in different states on the evolution of low-carbon behavior of governments and manufacturers. The study suggested that dynamic carbon tax and static subsidies are more advantageous for the low-carbon behavior of manufacturing enterprise. Chen and Hu [22] examined the carbon emission reduction behavior strategies of manufacturers and retailers from the perspective of negotiation power, considering the degree of consumer preference and concluded that consumers' low-carbon preference and carbon tax can stimulate manufacturers' low-carbon behavior. Chen and Hu [23] taking public participation into account and constructing a tripartite evolutionary game model consisting of governments, manufacturers, and the public. This model demonstrated a complementary and coordinated relationship between governments and the public in the evolution of low-carbon strategies.

However, the decision-making behaviors of different users are often challenging to analyze rationally due to the influence of irrational factors such as psychological perception and values [24]. Therefore, many researchers have incorporated prospect theory to account for decision makers' bounded rationality [25]. Prospect theory believes that individuals are finitely rational in the decision-making process, and the theory explains the mechanism of the role of finitely rational psychological factors and behavioral characteristics on the decision-makers choice of strategy, thus breaking the unreasonable assumption of entirely rational decision-makers. For instance, Duan et al. [26] employed prospect theory to demonstrate that incorporating perception parameters significantly impacts consumers' choices in promoting low-carbon buildings within the tripartite game model involving government, developers, and consumers. Gao et al. [27] also analyzed the game process of low-carbon strategy for enterprise and local governments based on prospect theory and highlighted that the environmental loss cost has a more significant influence on the low-carbon behavior of enterprise. In this study, the government, construction enterprise, and user groups are all limited rational decision-making subjects, aligning with the prospect theory's basic settings. Therefore, the prospect theory can be used to analyze the decision-making process of the user groups, especially the influence of government intervention policies and environmental regulations on the psychological perception of users and the degree of users' preference for low-carbon transportation infrastructure. In addition, Prospect Theory can also consider the influence of reference points to measure the different psychological perceptions and decision-making of the government, construction companies, and users under dual regulation with different needs for carbon emission reduction.

In summary, the majority of research on low-carbon strategy analysis has been concentrated in the power industry, tourism, and manufacturing sectors. However, there is limited research on the analysis of multi-principal strategies for carbon emission reduction during the construction of transportation infrastructure projects. Given the significance of transportation infrastructure projects as key contributors to carbon emissions, achieving low-carbon construction necessitates a collective effort from governments, construction companies, design companies, material suppliers, technology researchers and developers, user, and other stakeholders. Since transportation infrastructure projects often lack significant low-carbon characteristics and carbon labels, users are unable to determine whether these projects are genuinely low-carbon [28]. Considering the limitations of government regulatory behavior and the uncertainty of construction enterprise' low-carbon strategies, the current low-carbon behavior of transportation infrastructure construction enterprise is insufficiently binding, mainly guided by government regulation and supplemented by voluntary participation of relevant enterprise [29]. Promoting cooperation and joint supervision between the government, user, and construction enterprise is essential for enhancing environmental protection regulatory capacity and fostering low-carbon behaviors and decision-making among construction enterprise. Thinking about these questions in mind, this paper explores the interplay between the government and construction enterprise, while considering user as additional subjects striving towards a low-carbon goal. It constructed an evolutionary game model involving the government, construction enterprise, and user, based on the complex interactions among multi-interested stakeholders from both economic and game theory perspectives. Aiming to analyze the trends of strategic selection and behavioral changes among government, user, and construction enterprise in terms of carbon emission reduction in transportation infrastructure construction. The innovative contributions of this study are primarily reflected in the following aspects.

(1) Based on the characteristics of transportation infrastructure construction, this study simultaneously considers the dual constraints of government intervention and environmental regulation, integrates the dimensions of policy nature and economic instruments., and thoroughly investigates the impacts of multiple factors, such as carbon taxes, carbon subsidies, and penalty rules for environmental governance, on the selection of carbon emission reduction strategies by the relevant entities of transportation infrastructure construction. It broadens the perspective of behavioral analysis of carbon emission reduction strategy of transportation infrastructure.
(2) The users of transportation infrastructure as a third-party entity are included in the carbon emission reduction strategy game model between the government and construction enterprises. The complementary relationship between the government and users is examined for its potential role in encouraging enterprises to implement low-carbon transportation infrastructure construction strategies, thus expanding the traditional government-enterprise binary game framework. These innovations not only enrich the theoretical system in the carbon emission reduction strategy research field but also provide new insights for policy formulation in the practice of carbon emission reduction in transportation infrastructure construction.

2. Model assumptions and construction

2.1. Problem description

According to the role positioning and role in the development process of carbon emission reduction, the main subjects of carbon emission reduction in transportation infrastructure construction are divided into government, construction enterprise and user. The government, as the advocate of carbon emission reduction activities and the regulator of the low-carbon construction market, needs to make a trade-off between the industry's economic development and carbon emission reduction, and under the constraints of dual regulation, regulates the energy-saving and emission reduction behavior of the construction enterprise through carbon subsidies, carbon taxes, environmental pollution fines and other incentives and penalties, and incentivizes the user to travel in a low-carbon manner with the help of policy guidance and incentive subsidies to raise the public's awareness of low carbon and to change the existing high-carbon development model. The degree of user choice of low-carbon TI has an important impact on the government's decision-making, and user can put forward construction requirements to the government based on the use of transportation infrastructure selection [30]. With the proposal of green, low-carbon and high-quality development policies, as well as the user' personal experience of environmental degradation, the user' low-carbon awareness has increased and their preference for low-carbon products has changed. As user of transportation infrastructure, their direct experience and choice have a certain influence on the construction enterprise, therefore, user have a certain right to supervise the construction enterprise [31]. As the executor of transportation infrastructure construction, revenue is the main factor to be considered by construction enterprise, and the construction of low-carbon products needs to pay a certain incremental cost compared with the conventional transportation infrastructure, and the profit-seeking nature makes the construction enterprise have to consider the preference of user, government incentives, and penalties for environmental loss, etc., and decide whether to construct low-carbon products by comparing the benefits under different decisions. As a result, the logical relationship among governments, user and construction enterprise is shown in Fig. 1.

2.2. Model assumptions

Assumption 1. It is assumed that there are three stakeholders, i.e., government (G), construction enterprise (C), user (U), all of which have limited rationality characteristics, and each subject of the game adjusts its strategy based on the principle of maximizing its interests and eventually converges to a stabilization strategy over time evolution. The government has two strategies: "incentive" and "no incentive", with probabilities being x and 1-x respectively. The construction enterprise also has two strategies: "build low-carbon TI" and "build traditional TI", and the probability of construction enterprise building low-carbon Transportation is y, then the probability of building traditional TI is 1-y. Suppose the user's strategy is choosing low-carbon TI or traditional TI, then with probabilities z and 1-z, respectively. and both are functions of time, x, y, $z \in [0, 1]$.

Assumption 2. The primary revenue of a construction enterprise for building transportation infrastructure is represented by R_t, while the operation cost is denoted as C_{tg}, When construction enterprise constructs low-carbon transportation infrastructure, and the incremental cost generated by the construction of low-carbon products is C_{tl}, and the incremental cost mainly consists of the cost generated by low-carbon technology innovation, low-carbon material application, etc., and let S_{th} be the carbon subsidy that the construction enterprise receives from the construction of low-carbon products, t_1 be the uniform carbon tax rate levied by the government on the construction enterprise, t_2 be the carbon tax rate levied by the government on enterprise adopting low-carbon means, $t_1 > t_2$, the amount of CO_2 generated by constructing traditional products is E_1, the amount of CO_2 generated by constructing low-carbon products is E_2, and the carbon tax based on the carbon emissions and carbon tax rate is T=tE. When the construction enterprise adopts low-carbon behaviors in constructing low-carbon products, it can obtain a higher carbon quota and gain additional benefits as P_{tl}, and ε is the carbon emission reduction efficiency, and the construction enterprise The environmental benefit obtained through carbon emission reduction is $B=\varepsilon(E_1\text{-}E_2)$.

Assumption 3. Under environmental regulations and policy guidance, the government supervises construction enterprise. When the government provides policy incentives to cover regulatory costs for C_{g1}, and when such incentives are not provided for C_{g2}, the government can use feedback from user to make corresponding decisions regarding the construction of low-carbon products by these enterprise. The government selects policy incentives for construction enterprise to carry out low-carbon practices. By doing so, the government can build up social credibility for Q_g and provide corresponding incentives to user for A_g. If the government neglects to offer incentives, it may result in environmental losses for H_g, and the construction companies may be subjected to the cost of environmental regulation for F.

Assumption 4. The user, as the application terminal of transportation infrastructure, has a low-carbon awareness of σ and a preference for low-carbon products of δ. Under the government's policy guidance, when construction enterprise chooses to build low-carbon products, the user obtains an environmental benefit of P_{u1}. If construction enterprise builds traditional products, regardless of government incentives or no incentives, the negative comments of the user will cause damage to the honor of the enterprise D_u.

Assumption 5. Considering that the psychological perception elements of the decision-making subject may have an influence on

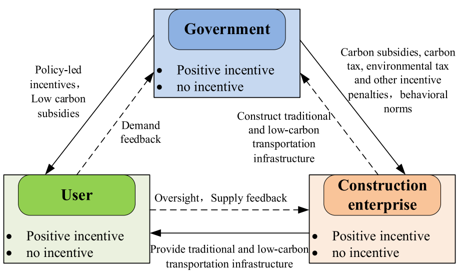

Fig. 1. Logical relationship diagram of the evolutionary game model of the three-party game.

behavioral decisions, the prospect theory co-proposed by Tversky and Kahneman is introduced [32], The utility model is replaced by the value function, with the relative value of perception $\Delta\pi$ used to represent perceived loss or gain. Additionally, the subjective probability weight function transforms the probability of the expected gain occurring into the weight [27], which can be calculated using Eq (1).

$$U = \sum w(p)V(\Delta\pi) \tag{1}$$

where p represents the likelihood of an event occurring ($0 < p < 1$); $w(p)$ signifies the weight or significance of the strategic decision maker's subjective judgment regarding the event, which can be calculated with Eq (2), γ denotes the risk coefficient that corresponds with the probability of the event happening, with the parameters of $w(1) = 1$ and $w(0) = 0$. The probability of events with varying levels of occurrence is weighted as either 1 or 0. Specifically, high probability events may be easily underestimated. When the probability of low probability events occurring is overestimated, which occurs when p is smaller, there is an increase in $w(p)$ compared to p. Conversely, when p is larger, there is a decrease in $w(p)$ compared to p. The subjective evaluation of the event's value by the decision maker is denoted by $V(\Delta\pi)$ and is typically calculated using Eq. (3) [24,33,34]. The coefficient of loss avoidance, λ, spans the range of $\lambda \geq 1$. Additionally, α and β are included. Technical term abbreviations will be explained upon their first usage. Adherence to conventional structure and grammatical accuracy are necessary.

$$w(p) = \frac{P^{\gamma}}{P^{\gamma} + (1-P)^{1/\gamma}} \tag{2}$$

$$V(\Delta\pi) = \begin{cases} \Delta\pi^{\alpha}, \Delta\pi \geq 0 \\ -\lambda(-\Delta\pi^{\alpha})^{\beta}, \Delta\pi < 0 \end{cases} \tag{3}$$

Based on the above assumptions, the relevant parameters and definitions involved in this paper are shown in Table 1.

2.3. Model construction

According to the prospect theory, the relevant decision makers will have a perception effect when they are uncertain about the loss and gain. This paper argues that there is uncertainty about the loss and gain of the damage to the government's social credibility and the honor of the enterprise. A perception effect characteristic is present, and there is a perception effect characteristic, from which the payment and gain matrix is constructed for the government, the construction enterprise and the user in the three parties as shown in Table 2.

3. Model and stabilization analysis

3.1. Analysis of the Government's strategic stabilization

For the government, E_{11} and E_{12} denote the expected utility on selecting "incentives" and "not incentives", and the Average expectation is expressed by $\overline{E_1}$,all of which are described as follows:

$$E_{11} = yz\left(V\left(Q_g\right) - A_g - C_{g1} - S_{th}\right) + y(1-z)\left(V\left(Q_g\right) - S_{th} - C_{g1}\right) + z(1-y)\left(V\left(Q_g\right) - C_{g1}\right) + (1-y)(1-z)\left(V\left(Q_g\right) - C_{g1}\right)$$

$$E_{12} = yz\left(-C_{g2}\right) + y(1-z)\left(-C_{g2}\right) + z(1-y)\left(-C_{g2} - H_g\right) + (1-y)(1-z)\left(-C_{g2} - H_g\right)$$

$$\overline{E}_1 = xE_{11} + (1-x)E_{12} = x(1-y)H_g + y\left(\left(-zA_g - S_{th}\right) - C_{g1} + C_{g2} + V\left(Q_g\right)\right) - (1-y)H_g - C_{g2}$$

The replicator dynamics equation of government's behavioral strategy is shown in the following:

$$F(x) = x\left(E_{11} - \overline{E_1}\right) = x(1-x)\left(y\left(-zA_g - H_g - S_{th}\right) + H_g - C_{g1} + C_{g2} + V\left(Q_g\right)\right)$$

Table 1
Model parameters and their definitions.

Symbol	Definition	Symbol	Definition
R_t	Basic Benefits of Construction enterprise	B	Environmental Benefits of Carbon Reduction Behavior in Construction Enterprise
C_{tg}	Construction Operating Costs	C_{g1}	Regulatory Costs of Government Incentives,
C_{tl}	Incremental cost of building low-carbon TI	C_{g2}	General Government Regulatory Costs,
S_{th}	Carbon Subsidy	Q_g	Government Social Credibility,
t	Carbon tax rate	A_g	Subsidies received by user
E	CO_2 emission	H_g	Environmental losses gained when government chooses not to incentivize
T_1	Carbon tax on ordinary construction TI	F	Environmental management fees levied by Construction Enterprise
T_2	Carbon tax on low-carbon construction TI	P_{ul}	Environmental gains received by user
P_{tl}	Additional revenue from building low carbon TI	D_u	Damage to corporate honor

Table 2
Payoff matrix of government, construction enterprise and user.

Government			User	
			Choose(z)	Not choose(1-z)
Construction enterprise	Build low-carbon TI (y)	Incentives(x)	R_t-C_{tg}-C_{tl} + S_{th}-T_2+P_{tl} + B, $V(Q_g)$-A_g-C_{g1}-S_{th}, A_g + P_{ul}	R_t-C_{tg}-C_{tl} + S_{th}-T_2+P_{tl} + B, $V(Q_g)$-C_{g1}-S_{th}, P_{ul}
		Not incentives(1-x)	R_t-C_{tg}-C_{tl} + P_{tl} + B, -C_{g2}, P_{ul}	R_t-C_{tg}-C_{tl} + P_{tl} + B, -C_{g2}, P_{ul}
	Build traditional TI (1-y)	Incentives(x)	R_t-C_{tg}-T_1-$V(D_u)$-F, $V(Q_g)$-C_{gl}, 0	R_t-C_{tg}-T_1-$V(D_u)$-F, $V(Q_g)$-C_{gl}, 0
		No incentives(1-x)	R_t-C_{tg} + $V(D_u)$-F, -C_{g2}-H_g, 0	R_t-C_{tg} + $V(D_u)$-F, -C_{g2}-H_g, 0

A first-order derivation of x yields:

$$dF(x)\,/\,d(x) = (1-2x)\big(y\big(-zA_g - H_g - S_{th2}\big) + H_g - C_{g1} + C_{g2} + V\big(Q_g\big)\big)$$

Hypothesis: $H(y) = y(-zA_g - H_g - S_{th}) + H_g - C_{g1} + C_{g2} + V(Q_g)$.

According to the stabilization theorem of differential equations. If $F(x) = 0$, then $dF(x)/d(x) < 0$, It means that the probability of the government selecting incentives is in a steady state. Since, $H(\mathrm{y})$ is a function that decreases as y increases. If $y = \frac{C_{g1} - H_g - C_{g2} - V(Q_g)}{-zA_g - H_g - S_{th}} = y^*$, $H(\mathrm{y}) = 0$, then, $F(x) = 0$, the government cannot determine the stabilization strategy, When $y < y^*$, $H(\mathrm{y}) > 0$, then $F(x) < 0$ and $x = 0$, $H(\mathrm{y}) = 0$, It means that $x = 1$ is the government's evolutionary stabilization strategy; Conversely, when $y > y^*$, $H(\mathrm{y}) < 0$, then, $F(x) > 0$, and $x = 1$, $H(\mathrm{y}) = 0$, that is, when $x = 0$, the government evolves a stable strategy, the stabilization evolution of the government strategy is illustrated in Fig. 2.

As presented in Fig. 2, the tangent plane intersects the point $(0, y = \frac{C_{g1} - H_g - C_{g2} - V(Q_g)}{-zA_g - H_g - S_{th}} = y^*, 0)$, with B_1 denoting the probability of the government implementing the incentive strategy, and V_{B_1} representing its volume. Similarly, B_2 refers to the probability of the government not adopting the incentive strategy, with V_{B_2} representing its volume, calculated as follows:

$$V_{B_1} = \int_0^1 \int_0^{\frac{H_g - C_{g1} + C_{g2} + V(Q_g)}{H_g + S_{th}}} \frac{C_{g1} - H_g - C_{g2} - V(Q_g)}{-zA_g - H_g - S_{th}} dzdy$$
$$= \frac{H_g - C_{g1} + C_{g2} + V(Q_g)}{A_g} \ln\left(\frac{A_g\left(H_g - C_{g1} + C_{g2} + V(Q_g)\right)}{(H_g + S_{th})} + 1\right)$$

$$V_{B_2} = 1 - V_{B_1} = 1 - \frac{H_g - C_{g1} + C_{g2} + V(Q_g)}{A_g} \ln\left(\frac{A_g\left(H_g - C_{g1} + C_{g2} + V(Q_g)\right)}{(H_g + S_{th})} + 1\right)$$

When $H_g + V(Q_g) = C_{g1} - C_{g2}$, the V_{B_2} achieves a maximum value of 1. It means that the government will not take incentives. When $Hg + V(Q_g) - C_{g1} + C_{g2} > 0$, The likelihood of the government implementing incentives is inversely related to the expenses associated with regulation, user subsidies, and carbon subsidies in the event of incentive implementation. Conversely, it is positively related to environmental losses, the government's credibility gains, and the government's regulatory expenses if incentives are not implemented. When regulatory, user, and carbon costs increase with the adoption of government incentives, the likelihood of implementation decreases due to fiscal pressures. The government's gained credibility is inversely proportional to the regulatory cost without incentives. As environmental protection becomes more crucial, pressure mounts for the government to regulate construction companies using incentives. When $Hg + V(Q_g) - C_{g1} + C_{g2} < 0$, and the environmental loss is extensive, it can be concluded that $Hg + V(Q_g) < 0$.This implies that $C_{g1} < C_{g2}$, indicating that the regulatory cost of the government to implement incentives is lower than the overall regulatory costs of the government. Consequently, the government incurs lower regulatory costs by providing incentives, thus enhancing the eagerness of enterprise to construct low-carbon transportation infrastructure.

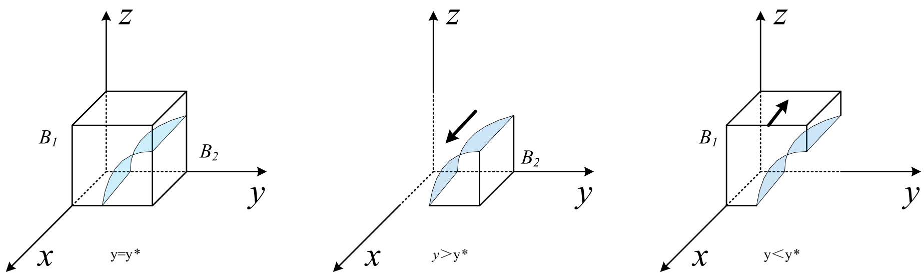

Fig. 2. Government strategy stabilization evolution phase diagram.

3.2. Analysis of the construction enterprise' strategic stabilization

The expected utility of the construction enterprise to construct low-carbon and conventional transportation infrastructure are denoted as E_{21} and $E_{22,}$ correspondingly. The average expected returns are denoted as $\overline{E_2}$ and are calculated through the following formula:

$$E_{21} = xz\left(R_t - C_{tg} - T_1 - V(D_u) - F\right) + x(1-z)\left(R_t - C_{tg} - T_1 - V(D_u) - F\right) + z(1-x)\left(R_t - C_{tg} + V(D_u) - F\right) + (1-x)(1-z)\left(R_t - C_{tg} + V(D_u) - F\right)$$

$$E_{22} = xz\left(R_t - C_{tg} - T_1 - V(D_u) - F\right) + x(1-z)\left(R_t - C_{tg} - T_1 - V(D_u) - F\right) + z(1-x)\left(R_t - C_{tg} + V(D_u) - F\right) + (1-x)(1-z)\left(R_t - C_{tg} + V(D_u) - F\right)$$

$$\overline{E}_2 = yE_{21} + (1-y)E_{22} = y(x(2V(D_u) + S_{th} + T_1 - T_2)) + F + P_{tl} - V(D_u) + B - C_{tl} + x(-2V(D_u) - T_1) - F + V(D_u) + R_t - C_{tg}$$

The replicator dynamics equation of construction enterprise's behavioral strategy is shown in the following:

$$F(y) = y(E_{21} - \overline{E_2}) = y(1-y)(x(2V(D_1) + S_{th} + T_1 - T_2) + F + P_t - V(D_1) + B - C_{tl})$$

A first-order derivation of y yields:

$$dF(y)\,/\,d(y) = (1-2y)(x(2V(D_u) + S_{th} + T_1 - T_2)) + F + P_t - V(D_u) + B - C_{tl}$$

Hypothesis: $G(x) = (x(2V(D_u) + S_{th} + T_1 - T_2)) + F + P_t - V(D_u) + B - C_{tl}$.

Due to $dG(x)/d(x) = 2V(D_u) + S_{th} + T_1 - T_2 > 0$, G(x) is an increasing function of x. When $x = \frac{C_{tl} - F - P + V(D_u) - B}{2V(D_u) + S_{th} + T_1 - T_2} = x^*$, $G(x) = 0$ and $F(y) = 0$, the construction enterprise is unable to determine the stabilization strategy. If $x > x^*$, then $G(x) > 0$, and $F(y) > 0$, when $y = 1$ and $F(y) = 0$, indicating that $y = 0$ is the evolutionary stabilization strategy of the construction enterprise. Conversely, if $x < x^*$, then, $G(x) < 0$ and $F(y) < 0$ when $y = 0$ and $F(y) = 0$, meaning that $y = 0$ is the evolutionary stabilization strategy of the construction enterprise, the stabilization evolution of the government strategy is illustrated in Fig. 3.

As shown in Fig. 3, A_1 represents the probability that a construction company builds a traditional transportation infrastructure, whose volume is denoted as V_{A_1}, and A_2 represents the probability that a construction company builds a low-carbon transportation infrastructure, whose volume is denoted as V_{A_2}, and the results of the calculation are as follows:

$$V_{A_1} = \int_0^1 \int_0^1 \frac{C_t - F - P_t + V(D_u) - B}{2V(D_u) + S_{th} + T_1 - T_2} dz dx = \frac{C_t - F - P_t + V(D_u) - B}{2V(D_u) + S_{th} + T_1 - T_2}$$

$$V_{A_2} = 1 - V_{A_1} = 1 - \frac{C_t - F - P_{tl} + V(D_u) - B}{2V(D_{11}) + S_{th} + T_1 - T_2}$$

When $C_{tl} = B + F + P_{tl} - V(D_u)$, the probability that an enterprise chooses to build low-carbon transportation infrastructure is equal to 1, i.e., the incremental cost for an enterprise to build low-carbon transportation infrastructure is equal to the sum of its additional benefits, environmental benefits, and environmental governance fees levied if it does not build and the enterprise's gain of honor, and the construction enterprise will prefer to build traditional transportation infrastructure when the cost is moderate. When the two conditions are not the same, the probability of an enterprise building low-carbon transportation infrastructure decreases as the incremental cost and loss of reputation incurred by the enterprise increases. Conversely, the probability increases as the difference ($T_1 - T_2$) between the additional benefits, environmental benefits, environmental governance fees imposed for not constructing, carbon subsidies, and carbon taxes increases. As the incremental cost of building low-carbon transportation infrastructure rises, the government can encourage the enterprise's low-carbon construction behavior by boosting carbon subsidies and offering other incentives. Lowering the carbon tax rate for low-carbon construction enterprise, while simultaneously increasing the tax rate for enterprise constructing ordinary transportation infrastructure, can effectively encourage construction companies to adopt low-carbon practices. This approach promotes sustainable building behavior among construction enterprise.

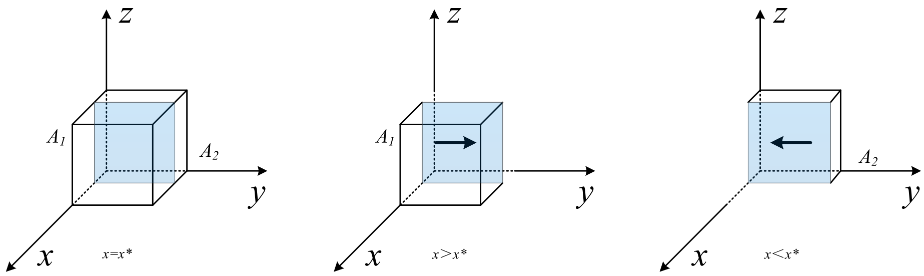

Fig. 3. Construct enterprise strategy stabilization evolution phase diagram.

3.3. Analysis of the user' strategic stabilization

The expected utility of user choosing and not choosing low-carbon transportation infrastructure are denoted by E_{31} and E_{32}, respectively, and the average expected benefits are denoted by $\overline{E_3}$, which are calculated by the following formulas:

$$E_{31} = xy(A_g + P_{1u}) + y(1-x)P_{ul}$$

$$E_{32} = xyP_{ul} + y(1-x)P_{ul}$$

$$\overline{E}_3 = zE_{31} + (1-z)E_{32} = xyzA_g + yP_{ul}$$

The replicator dynamics equation of user's behavioral strategy is shown in the following:

$$F(z) = z(E_{31} - \overline{E_3}) = z(1-z)xyA_g$$

A first-order derivation of z yields:

$$dF(z) / d(z) = (1-2z)xyA_g$$

Set : $T(x) = xyA_g$.

Due to $dT(x)/d(x) = yA_g > 0$, $T(x)$ is an increasing function of x. Thus, when $x = A_g = 0 = x^*$, $T(x) = 0$,and $F(z) = 0$ is constant. This indicates that the user cannot determine the stabilization policy. When $x > x^*$, $T(x) > 0$, then $F(z)$ becomes less than 0, and $z = 1$. $F(z) = 0$, which means that $z = 1$ represents the user's evolution stabilization policy. When $x < x^*$, $T(x) < 0$, then $F(z)$ becomes greater than 0, and $z = 0$, $F(z) = 0$, indicating that $z = 0$ represents the user evolution stabilization policy, the stabilization evolution of the government strategy is illustrated in Fig. 4.

As shown in Fig. 4, C_1 represents the probability that the user does not choose low-carbon Transportation infrastructure, whose volume is V_{C_1}, and C_2 represents the probability that the user chooses low-carbon Transportation infrastructure, whose volume is denoted as V_{C_2}, which is calculated as follows:

$$V_{C_1} = \int_0^1 \int_0^1 A_g dzdy = A_g$$

$$V_{C_2} = 1 - V_{C_1} = 1 - A_g$$

Under the dual regulation of environmental policies and government interventions, the user as a third-party objective subject, willingness to choose low-carbon transportation infrastructure is only positively correlated with the subsidy Ag that the user can obtain from government. This pertains to the public demand characteristics of transportation infrastructure. Namely, it lacks significant low-carbon features and corresponding labeling. Regardless of whether the infrastructure is considered low-carbon, its convenience remains a decisive factor for user in selecting the appropriate transportation infrastructure. This aligns with actual consumer behavior. Therefore, to address the lack of user attention towards Transportation infrastructure constructed by enterprise, the government or relevant departments should enhance publicity on the benefits of low-carbon TI applications and low-carbon aspects at the outset. This would improve user awareness, enhance the degree of low-carbon preference, and promote user participation in the initiative.

3.4. Stabilization analysis of equilibrium point and strategy combination of tripartite evolutionary game system

Based on the principle of differential equation stabilization, the dynamic equations of the government, construction companies, and user are resolved. It is evident that the equilibrium points of the evolutionary game system are derived as [0,0,0] [1,0,0], [0,1,0], [0,0,1] [1,1,0], [1,0,1], [0,1,1], and [1,1,1] when $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$. According to the Lyapunov correlation theory and the stabilization analysis results of the three-party strategy, we constructed the Jacobian matrix for the three-party evolutionary game system.

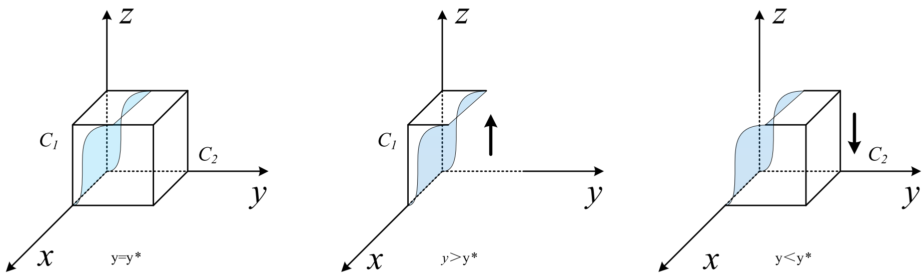

Fig. 4. User policy stabilization evolution phase diagram.

$$A = \left\{ \begin{array}{ccc} (1-2x)\left(H_g - C_{g1} + C_{g2} + V\left(Q_g\right)\right) - 2y\left(zA_g + H_g + S_{th}\right) & x(x-1)\left(zA_g + H_g + S_{th}\right) & xyA_g \\ y(1-y)\left(2V\left(D_u\right) + S_{th} + T_1 - T_2\right) & (1-2y)\left(x\left(2V\left(D_u\right) + S_{th} + T_1 - T_2\right) + F + P_{tl} - V\left(D_u\right) + B - C_{tl}\right) & 0 \\ 2yz(1-z)A_g & 2z(1-z)\left(xyA_g + yP_{ul}\right) & 2(1-z)\left(xyA_g + yP_{ul}\right) \end{array} \right\}$$

The above equilibrium points are substituted into Jacobi matrix to calculate the corresponding eigenvalues, and the stabilization of each equilibrium point is determined based on the positive and negative characteristic root. When all the eigenvalues of the Jacobi matrix are negative, the system is in the state of evolutionary stable strategy; When the eigenvalues possess one or more positive real parts, the equilibrium point is unstable, When the eigenvalues contain zeros, the stabilization of the equilibrium point is uncertain, and the equilibrium point needs to be analyzed specifically by scenarios. The eigenvalues of the Jacobi matrix for each equilibrium weight point are presented in Table 3.

From the stabilization analysis results in Table 3, when $V(Q_g) < S_{th} - C_{g2} + A_g + C_{g1}$ and $T_2 - T_1 - V(D_u) - F < B - C_{t1} + P_{tl}$, all eigenvalues of the Jacobi matrix at the equilibrium point [1,1,1] are less than 0. Indicating that the point is a stable equilibrium of the system. At this point, the credibility benefit gained by the government is greater than the sum of the incremental cost of government regulation ($C_{g1} - C_{g2}$) and the subsidies given by the government to the user and the carbon subsidies of the enterprise. When $V(Q_g) > S_{th} - C_{g2} + A_g + C_{g1}$ and $V(D_u) - F < B - C_{t1} + P_{tl}$, the eigenvalues of the Jacobi matrix at the equilibrium point [0, 1, 1] are all less than 0, indicating that this point is another asymptotic stabilization point of the system, in which the credibility benefits gained by the government are greater than the subsidies that the government needs to pay to the enterprise and user as well as the incremental cost of regulation when the government adopts incentives versus the incremental cost of regulation when it does not adopt incentives.

The analysis of system stabilization points revealed the existence of two combinations of evolutionary stable strategies for the replicated dynamic equation system: one involving government incentives, enterprise construction, and user choice, and the other involving enterprise construction and user choice without government incentives. Whether the government will implement an incentive strategy depends on its current stage of development. In the early stages of development, the government faces significant pressure from societal opinions and environmental degradation. To encourage the emergence of a stable strategic combination involving government incentives, enterprise construction, and user choice, the government may implement regulations that bolster the incentives and penalties imposed on enterprise constructing low-carbon transportation infrastructure. Large enough incentives and penalties should be set to fully utilize the incentive and penalty mechanism. The government could implement regulations to enhance incentives and penalties for companies to construct low-carbon transportation infrastructure. The amounts of incentives and penalties should be substantial enough to fully utilize the incentive mechanism. By providing targeted financial incentives, the government can stimulate the demand for low-carbon transportation infrastructure, leading construction enterprise to reap greater profits. This in turn bolsters their motivation to invest in constructing such infrastructure. Under government policies and environmental regulations, the industry has grown to a significant size, resulting in the establishment of a relatively perfect low-carbon transportation infrastructure construction and operating system in the market. However, excessive government intervention increases financial burdens, leading to the need for withdrawing from the market. Eventually, the government adopts a strategy of not implementing incentives.

4. Simulation analysis

In order to more clearly and intuitively to illustrate the dynamic evolution process of government, construction enterprise and user's systems under the dual regulation, and explore strategies to achieve stabilization. After conducting an extensive review of the relevant studies and combining the stabilization of the three-party strategy mentioned above, we refer to various sources including the 2015 National Green Building Evaluation Mark Statistical Report, China Carbon Tax Framework Design Special Report, and China Energy Statistical Yearbook to assign reasonable values to parameters. Based on the fulfillment of the hypothetical model and the actual conditions, we apply MATLAB 2022a to numerically simulate the model and analyze the influence of important factors on the evolutionary game process and the stabilization of the system.

Table 3
Stabilization analysis of characteristic roots and equilibrium points.

Equalization point	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3	Real part symbol	Stabilization conclusion
[0,0,0]	0	$C_{g2} - H_g + C_{g1} + V(Q_g)$	$B - C_{tl} + F + P_{tl} - V(D_u)$	(0, -, +)	Uncertainty
[1,0,0]	0	$C_{g2} - H_g - C_{g1} - V(Q_g)$	$B - C_{tl} + F + P_{tl} + V(D_u) + S_{th} + T_1 - T_2$	(0, -, +)	Uncertainty
[0,1,0]	$2P_{ul}$	$C_{g2} - S_{th} - C_{g1} - V(Q_g)$	$C_{tl} - B - F - P_{tl} + V(D_u)$	(+, ×, +)	Uncertainty
[0,0,1]	0	$C_{g2} + H_g - C_{g1} + V(Q_g)$	$B - C_{tl} + F + P_{tl} - V(D_u)$	(0, +, ×)	Uncertainty
[1,1,0]	$2P_{ul} + 2A_g$	$C_{g1} + S_{th} - C_{g2} - V(Q_g)$	$C_{tl} - B - F - P_{tl} - V(D_u) - S_{th} - T_1 + T_2$	(+, ×, +)	Uncertainty
[1,0,1]	0	$C_{g1} - H_g - C_{g2} - V(Q_g)$	$B - C_{tl} + F + P_{tl} + V(D_u) + S_{th} + T_1 - T_2$	(0, -, ×)	Uncertainty
[0,1,1]	$-2P_{ul}$	$C_{g2} - A_g - C_{g1} - S_{th} + V(Q_g)$	$C_{tl} - B - F - P_{tl} + V(D_u)$	(-, -, -)	ESS
[1,1,1]	$-2P_{ul} - 2A_g$	$S_{th} - C_{g2} + A_g + C_{g1} - V(Q_g)$	$C_{tl} - B - F - P_{tl} - V(D_u) - S_{th} - T_1 + T_2$	(-, -, -)	ESS

* "+" denotes greater than zero; "-" denotes less than zero; "0″ denotes uncertainty, "ESS" denotes Evolutionarily Stable Strategy,① $V(Q_g) < S_{th} - C_{g2} + A_g + C_{g1}$, $T_2 - T_1 - V(D_u) - F < B - C_{t1} + P_{tl}$;② $V(Q_g) > S_{th} - C_{g2} + A_g + C_{g1}$, $V(D_u) - F < B - C_{t1} + P_{tl}$.

4.1. Simulation analysis of stabilization point

According to the evolutionary game system strategy stabilization condition ①, initial parameters are assigned values solely for the analysis of their influence on the evolutionary results, and are not representative of actual gains. Refer to the relevant literature [35, 36], make an initial assignment to the parameters as: $C_{g1} = 6$, $C_{g2} = 10$, $H_g = 3$, $V(Q_g) = 2$, $A_g = 4$, $S_{th} = 3$, $B = 4$, $C_{tl} = 2$, $F = 2$, $P_{tl} = 4$, $V(D_u) = -4$, $T_1 = 2$, $T_2 = 1$, $P_{ul} = 5$. The dynamic equations were then simulated 50 times for analysis. As depicted in Fig. 5, the evolutionary game system ought to be in its initial stages of development during the dynamic transformation process as a result of the introduction of "dual-carbon goals" and environmental regulations. Consequently, the government is confronted with environmental challenges and intends to provide incentives, including rewards and penalties, to encourage businesses to invest in low-carbon transportation infrastructure. At this stage, the user selects a stable combination strategy of (1, 1, 1).

According to stabilization condition ②, seting array 2: $C_{g1} = 4$, $C_{g2} = 10$, $H_g = 3$, $V(Q_g) = 2$, $A_g = 5$, $S_{th} = 3$, $B = 2$, $C_{tl} = 8$, $F = 1$, $P_{tl} = 4$, $V(D_u) = -4$, $T_1 = 2$, $T_2 = 1$, $P_{ul} = 5$. The simulation of replicated dynamic equations is then conducted 50 times. Fig. 6 shows that the user's low-carbon awareness increases as the evolutionary stage matures. In order to comply with state subsidies and policy guidance, the enterprise independently pursues low-carbon construction. The government is gradually withdrawing from the market and instead using a strategy to stabilize the combination point (0, 1, 1). However, due to the current situation of the construction market, achieving this stabilization strategy in reality is challenging because China is currently in the stage of economic transformation. The objective of the enterprise is to make profits. It is difficult for enterprise to independently build low-carbon transportation infrastructure without government incentives. Thus, presently the government should regulate the evolution process effectively to ensure timely and appropriate rewards and punishments, safeguarding the interests of construction enterprise and user while encouraging the transition towards a low-carbon construction market.

4.2. Simulation analysis of main influencing factors

Combining the above equilibrium stabilization theory analysis and simulation, [government incentives, enterprise construction, user choice] strategy combination is the ideal state to promote the development of the current low-carbon construction market. When condition ① is satisfied, the evolutionary game system is evolutionarily stable (1,1,1). Based on this scenario, the baseline parameter is used as the basis. The parameter values are varied up and down to simulate and study the impacts of the changes in the values of the critical influencing factors A_g, C_{tl}, H_g, P_{tl}, Q_g, S_{th}, T_1, T_2 on the low-carbon strategies of the government, construction enterprise, and user.

(1) The influence of subsidies received by user (A_g) and low-carbon subsidies (S_{th}) on system evolution

Under the premise of Keeping other parameters unchanged, analyze the dynamic evolution path of stabilization strategy under varying user subsidies. Set the initial value of user subsidies (A_g) to 4, 1 and 7 respectively, and the dynamic replication equation evolves 50 times over time. The strategy evolution path of the three players is shown in Fig. 7.

As illustrated in Fig. 7, when the value of A_g increases, user are more likely to choose low-carbon transportation infrastructure, however, the probability of the government taking incentive measures decreases. Additionally, when the A_g value at a certain threshold, the government prefers the approach of refraining from using incentives. It is evident that increasing user subsidies can place a huge financial burden on the government, which may lead to the cancellation of said subsidies. Therefore, when formulating subsidy policies, the government should carefully consider its financial situation to prevent undue financial strain in the future. Concurrently, the government may explore alternative strategies to incentivize consumers to purchase low-carbon goods.

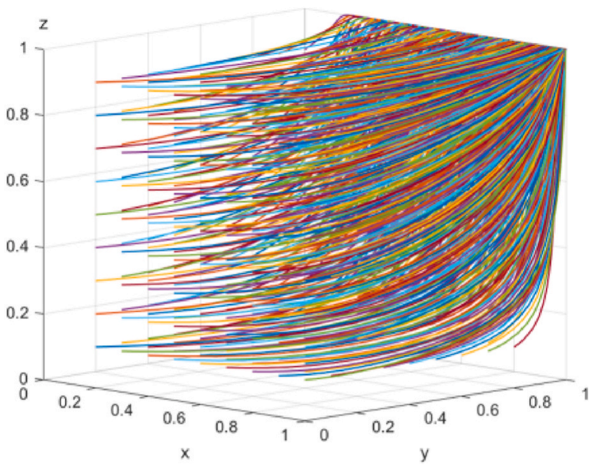

Fig. 5. Array 1 evolves the result 50 times.

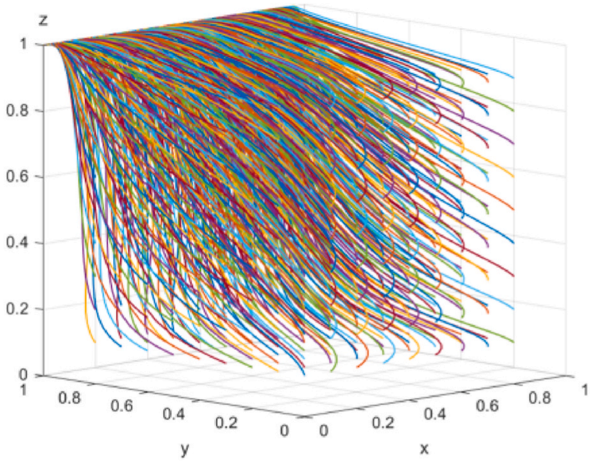

Fig. 6. Array 2 evolves the result 50 times.

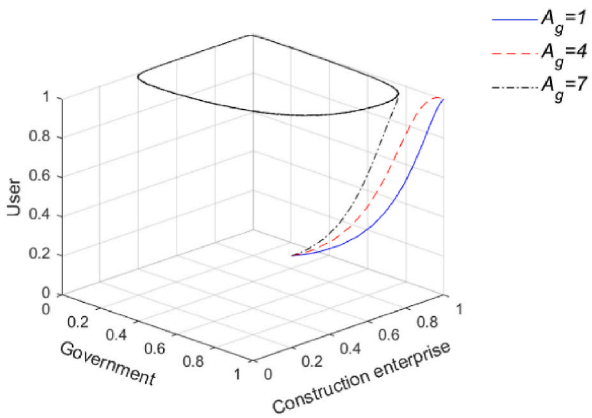

Fig. 7. The impact of user subsidies.

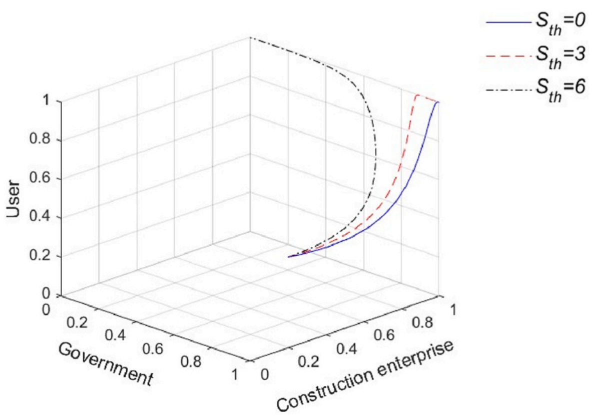

Fig. 8. The impact of carbon subsidies.

Similarly, the parameter values of S_{th} are set to 0, 3 and 6, respectively while other parameters remain constant, the simulation results are shown in Fig. 8, When S_{th} value is small during the evolution process, the chance of construction enterprise selecting the low-carbon transportation infrastructure strategy decreases. However, as the parameter values of S_{th} increasing, the strategy of construction enterprise becomes unstable. This suggests that solely increasing the low-carbon subsidy cannot facilitate the construction enterprise's decision to opt for low-carbon construction. The low-carbon subsidy is inversely proportional to the probability of the government's choice of incentives. When the S_{th} value reaches 6, the government's strategy changes from 1 to 0, which aligns with the observed impact of user subsidies. Consequently, when the government establishes a justifiable carbon subsidy, it must enhance the penalty and consider various factors. This approach supports enterprise in selecting low-carbon construction strategies.

(2) The influence of environmental loss (H_g), incremental cost (C_{tl}), additional revenue (P_{t1}) and government social credibility (Q_g) on system evolution

The parameter values of Hg are set 0, 3 and 6, respectively, while other parameters remain constant, to explore the influence of the change of environmental loss on the dynamic evolution process. As shown in Fig. 9, The environmental loss has a certain influence on the evolutionary relationship among the multi-stakeholders. However, the impact effect varies periodically. As the value of Hg increases, the cycle time becomes longer, making it harder for the strategy selection to converge on stabilization. Therefore, merely controlling the factor H_g will not bring strategies of relevant stakeholders tending to stabilization. To achieve the optimal combination of stabilized low-carbon strategies, a comprehensive examination of multiple factors is indispensable.

Similarly, while keeping other parameters unchanged, assigning values of C_{tl} to 4, 8 and 12, respectively. The probability of enterprise selecting low-carbon construction decreases with the increase of C_{tl}, while the likelihood of government incentives adoption escalates. As illustrated in Fig. 10, when C_{tl} elevates from 4 to 12, the enterprise's strategic orientation shifts from low-carbon construction to traditional construction. Consequently, the probability of user' preference for low-carbon options alters from 1 to 0.6. These findings underscore the crucial role of incremental costs in shaping the enterprise's low-carbon strategy, and thereby, reducing incremental costs becomes essential to achieve a low-carbon stable strategy portfolio. Construction companies should persistently enhance technological innovation to mitigate the incremental expenses associated with low-carbon construction. Concurrently, the government should formulate low-carbon policies, reinforce low-carbon guidance, and provide appropriate low-carbon subsidies to offset a portion of the incremental costs of low-carbon construction. Moreover, it should focus on enhancing the additional benefits of low-carbon construction in the operation of the construction market to stimulate the implementation of enterprise' low-carbon transportation infrastructure strategies. When the amount of carbon subsidies exceeds the incremental costs of low-carbon construction or becomes equivalent, the greater is the propensity of construction enterprise to opt for low-carbon transportation infrastructure development.

The assigned values for P_{tl} are 0, 4, and 8, as depicted in Fig. 11. When P_{tl} is zero, the probability of the enterprise participating in low-carbon construction is minimal. However, as the values of P_{tl} increasing, when P_{tl} increases to 8 , the enterprise's strategy progressively stabilizes, and transitioning from traditional construction to low-carbon construction. This indicates that the additional revenue is a crucial influencing factor in an enterprise's selection of low-carbon construction strategy. Moreover, as P_{tl} increases, the likelihood of the government opting for an incentive strategy diminishes, which is consistent with reality. When the enterprise's benefits are substantial enough, even in the absence of government-related policy incentives, it will still lean towards low-carbon construction. Consequently, enhancing low-carbon publicity, elevating low-carbon awareness, and augmenting the extra benefit of low-carbon construction are effective strategies to promote the enterprise's choice of low-carbon construction strategy.

Similarly, Q_g is assigned values of 0, 2, and 4 respectively. As depicted in Fig. 12, an increase in government credibility leads to a faster adoption rate of incentive strategies by the government. However, when Q_g has a small value, both enterprise and governments exhibit unstable strategy choices, while user are less influenced by changes in government credibility. This suggests that user primarily focus on tangible benefits and interests offered by the government when evaluating its credibility. Therefore, enhancing government credibility alongside providing increased financial subsidies to enterprise and user can effectively promote the implementation of low-carbon behavior strategies.

(3) The influence of carbon tax(T) on system evolution

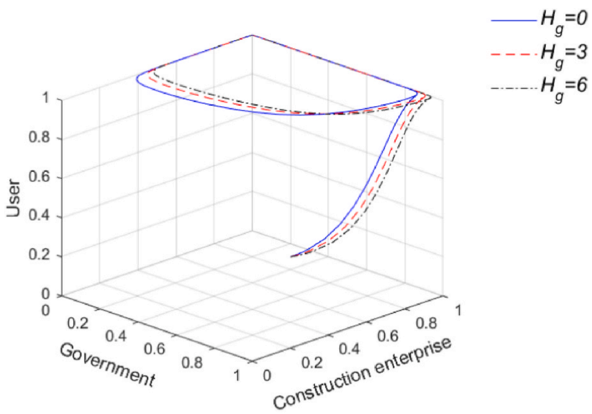

Fig. 9. The impact of environmental loss.

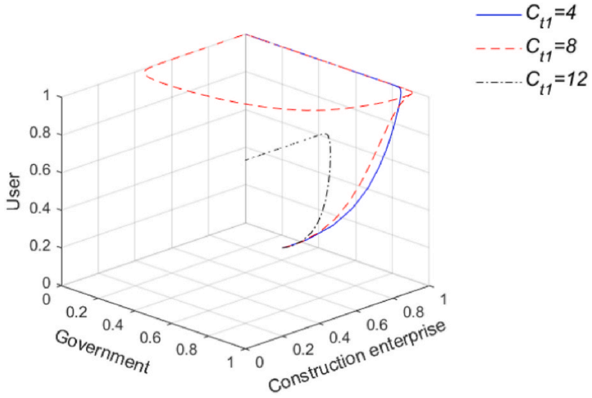

Fig. 10. The impact of incremental cost of building low-carbon products.

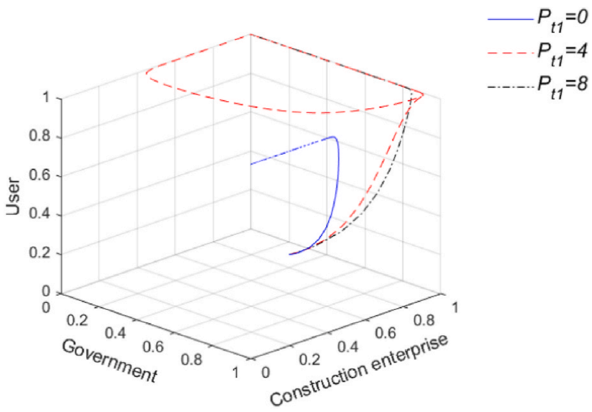

Fig. 11. The impact of additional revenue from low-carbon products.

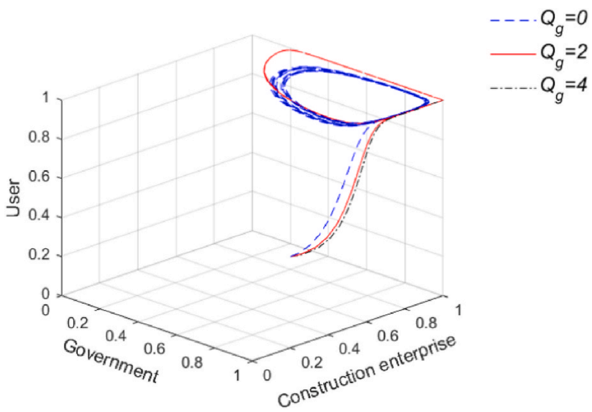

Fig. 12. Government credibility impact.

Figss. 13–14 reflects the impact of carbon tax on the dynamic evolution process. Assign values of 2, 4, and 6 to T_1 respectively. As shown in Fig. 13, when the carbon tax on traditional construction is low, both enterprise and government strategies are unstable. When $T_1 = 6$, the government's strategy tends towards a stable state with disincentives. This indicates that while carbon tax collection benefits the government financially, for higher amounts levied on ordinary construction, the government tends to choose disincentives. However, enterprise may still opt for low-carbon construction due to cost pressures. In Fig. 14 where values of 0, 1 and 2 are assigned to low-carbon construction carbon tax T_2; changing the values of T_2 have little impact on Stakeholders' evolution strategy which remains unstable.

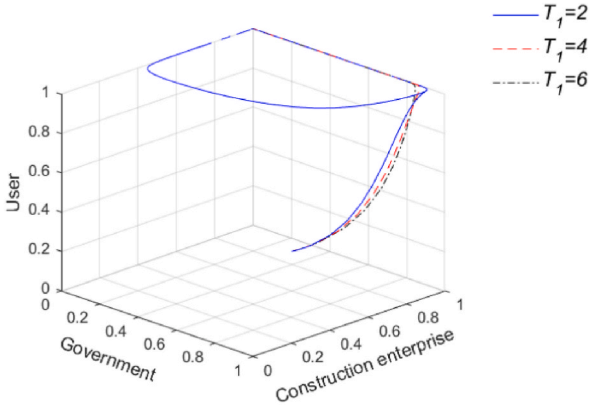

Fig. 13. The impact of carbon taxes on common products.

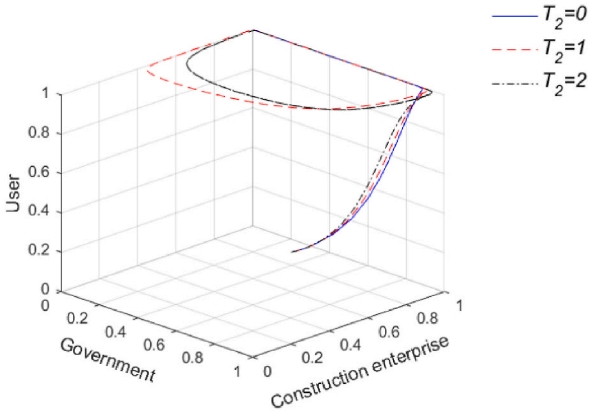

Fig. 14. The impact of carbon tax on low-carbon products.

Comparing Figs. 13 and 14, Indicates that when the government increases carbon taxes on traditional construction while lowering them for low-carbon alternatives (T_2), there is a greater likelihood that enterprise will adopt low-carbon strategies instead. The greater the discrepancy between these two taxes ($T_1 - T_2$), the faster enterprise tend towards stabilizing their adoption of low-carbon practices through this gradient approach which effectively promotes combining such strategies with traditional ones.

5. Conclusion

The study focuses on a transportation infrastructure construction project, considering the effects of dual regulation from government policy guidance and environmental constraints on low-carbon strategies adopted by the government, construction companies, and user. A tripartite dynamic evolutionary game model is constructed between the government, construction enterprise and user to examine the stabilization and combination strategies of all parties involved. Furthermore, through modeling, this study examines how carbon tax, carbon subsidies, environmental governance measures, and user preferences impact main strategies. By validating our hypothetical model and deriving conditions for strategy stabilization, our team provides recommendations on how to improve these influential factors. The principal findings are as follows.

(1) The probability of the government adopting incentives , in addition to user low-carbon preference. is also affected by the regulatory costs, carbon subsidies, user subsidies, environmental losses, and government credibility. The regulatory cost is a crucial factor that determines whether the government provides incentives. However, due to the timeliness of government regulation and the complexity of the procedure leads to the uncertainty of the regulatory cost. Hence, the government, on the basis of controlling its own regulatory cost, reasonably formulates the amount of carbon subsidy, refines the regulatory rules, and simultaneously maximizes effectiveness of the user's supplemental regulation. Additionally, the government employs suitable incentives tailored to the specific circumstances, thereby facilitating the enterprise's carbon Emission reduction behavior occurs. The low-carbon construction offers the benefit of environmental protection, energy conservation, and emission reduction. However, relying only on the market regulation mechanism is difficult to achieve the low-carbon development of

transportation infrastructure construction. The government should play a regulatory and incentive role to promote the scale and sustainable development of low-carbon transportation infrastructure construction.

(2) The decision of enterprise to construct low-carbon transportation infrastructure is primarily influenced by factors such as carbon subsidies, variations in carbon tax rates, losses of enterprise honor, environmental governance fees, incremental costs associated with low-carbon construction, additional benefits, and environmental gains. The probability of building low-carbon transportation infrastructure is found to be weakly correlated with user strategy choices but negatively correlated with incremental costs and enterprise honor loss. Conversely, it shows a positive correlation with additional benefits, environmental gains, environmental governance fees, carbon subsidies and differences in carbon tax rates. Nevertheless, the primary hindrance to the low-carbon behavior of enterprise is the incremental cost, Consequently, enhancing the extra benefits, reducing the incremental cost and increasing the difference of carbon tax are effective ways to motivate enterprise to build low-carbon transportation infrastructure. Furthermore, it is crucial to enhance the promotion of low-carbon practices among construction personnel, raise awareness about low-carbon construction, facilitate the adoption of low-carbon technologies, enhance the low-carbon competitiveness of enterprise, and promoting the sustainable development of the enterprise's low-carbon construction.

(3) The strategy of user selecting low-carbon transportation infrastructure is positively correlated with the subsidies received from government, less affected by the environmental benefits. Based on the public service characteristics and irreplaceability of transportation infrastructure, enhance user' awareness of low-carbon practices and focus on guiding their low-carbon behaviors is necessary to user making more informed choices regarding low-carbon strategies. Additionally, the user serves as a supplementary element in the supervisory relationship between the government and the enterprise. The low-cost supervision of user can effectively compensates for the defects of the government's supervision of the higher cost. This facilitates the establishment and enhancement of social participation in the low-carbon supervision system, thereby promoting the progress of low-carbon construction in transportation infrastructure projects.

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Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Yinghui Zhang: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Yun Chen:** Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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