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Research Article

Evolutionary Game Model of Civil Aviation and High-Speed Rail Interaction Strategies Based on the Passenger Ticket and Carbon Trading Prices

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This study elaborated an evolutionary game model to optimize the decision-making process on the interaction between civil aviation and high-speed rail under alternative passenger ticket prices (PTPs) and carbon trading prices (CTPs). First, a logit model was used to calculate the passenger flow distribution rate in civil aviation and HSR, and their revenue loss function was determined according to varying PTPs and CTPs. Second, an evolutionary game model with incomplete information was developed to assess the respective revenues. Third, the stable strategy solution of the game model was derived from replicator dynamics, and an investigation of stable conditions under variable cases was performed. Finally, the simulation of a case study on the Beijing–Shanghai corridor was conducted to validate the proposed model's feasibility. The additional revenue is shown to be the key influencing factor, mainly controlling the strategic decisions of airport and high-speed rail companies. Besides, the final strategy was strongly influenced by the alteration of PTPs and CTPs: higher PTPs promoted civil aviation and high-speed rail collaboration, while increased CTPs forced their competing behavior. The results obtained are instrumental in outlining the optimal strategy range for passenger ticket and carbon trading prices, encouraging high-speed transportation system growth.

1. Introduction

Civil aviation and high-speed rail (HSR) have become the two main operators in the high-speed transportation market [1–4]. Inevitably, these two transportation modes coexist in some major passenger corridors, with both competitive and cooperative relationships [5]. The passenger ticket mechanism, market structure strategy of civil aviation, and HSR, as well as the travel choice behavior of passengers, will affect their passenger allocation and revenue for the same passenger flow corridor. Simultaneously, these two transportation modes require large inputs of energy and resources with significant carbon emissions, which relate to revenue for airports and rail companies (Frederico et al., 2023) [6]. In this paper, we suppose civil aviation and HSR are two independent game players that can substitute government for decision-making behavior. Since game theory has been widely applied to help explain how cooperative behavior is promoted in human societies, evolutionary game theory is a useful tool for analyzing interactions between two or more players [7]. Therefore, analyzing the game dynamics based on strategies under different passenger ticket prices (PTPs) and carbon trading prices (CTPs) between civil aviation and HSR is vital to guide policies and recommendations for a balanced market.

The main contribution of this paper was to present a two-dimensional dynamical system by applying the logit model and utility function to reveal the coupling relationship between civil aviation and HSR under different passenger ticket and carbon trading prices. The most important contributions of this paper are (i) the development of a logit model to measure market share with consideration of passenger ticket, speed, comfort, safety, and accessibility and (2) the creation of the evolutionary game model to analyze the revenue between competition and cooperation based on the PTPs and CTPs. Finally, an illustrative case of the Beijing–Shanghai corridor was carried out to prove our applicability by comparing the difference in additional profit of a combination of six strategies. This study could be an effective tool for transport authorities to measure airport and rail companies' comprehensive operation efficiency and help them design a clear and straightforward management strategy for the transportation sector.

The rest of this paper is organized as follows. Section 2 reviews the related literature. Sections 3 and 4 describe the logit model and methodology of the evolutionary game. Section 5 analyzes the model and discusses its stability in six scenarios. Section 6 estimates the civil aviation and HSR operating revenues of the Beijing–Shanghai corridor and compares them with different PTPs and CTPs. Finally, the main findings, conclusions, and future work are provided in Section 7.

2. Literature Review

The available literature on competition and collaboration between civil aviation and high-speed rail (HSR) is briefly surveyed in Section 2.1, with an emphasis on the limitations and existing analytical gaps. Section 2.2 focuses on available methodologies for assessing the effect of carbon dioxide emissions on transportation, their limitations in considering the environmental effects on these two transportation modes, and the proposed solutions for mitigating these problems.

2.1. Civil Aviation and HSR. Over the past few decades, numerous research studies have examined the competition between civil aviation and HSR in most countries globally. Our research expands on previous work investigating the intermodal connections between civil aviation and HSR using an evolutionary game theory model. The effects of competition between civil aviation and HSR have been studied in a category of literature. Talebian and Zou [5] reported that, given the available high-speed infrastructure, HSR could be the optimal technology option to compete with civil aviation. Jiang and Zhang [8] studied the HSR effect on airports' long-lasting strategies and reported that civil aviation was more likely to turn to a hub-and-spoke network confronted with fiercer competition. Yang and Zhang [9] claimed that flight fare, or PTP for civil aviation, as well as HSR fare, decreased along with the rising weight of social welfare in HSR's objective function. Luo et al. [10] constructed a two-stage air-rail evolutionary game model, which simulation revealed that a travel distance range of 650–850 km was the fiercest competitive zone for civil aviation and HSR.

Another group of researchers analyzed the collaboration between civil aviation and HSR. Takebayashi [11, 12] investigated the potential for civil aviation-HSR collaboration, proved that the connection between railway companies and small airports eased congestion at large-scale airports, and addressed the issue of civil aviation strategies, showing that airports could be more profitable if they had a hub location. Jiang and Zhang [13] studied the welfare effects of air-HSR collaboration and reported that expanding the share of welfare tickets was highly beneficial under an effective alternative mode and sufficient hub airport capacity. Li et al. [14] analyzed the effects of collaboration, interairport relationships, and ownership issues in a multiairport and revealed that subsidies to air-rail service would benefit both passengers using the air-HSR service and those who choose to persist in using direct air service.

However, there are several significant gaps in previous theoretical research on air-HSR interactions.

First, some studies suppose that civil aviation and HSR greatly differ at the lateral level [5, 8, 9, 13]. D'Alfonso et al. [15] and Socorro and Viecens [16] also have similar approaches to this issue. However, some practical surveys have shown that air-HSR is more suitable for distinguishing at the vertical level. According to Yamaguchi et al. (2008), in Japan's transportation market, HSR achieved a dominant position below a 700 km travel distance, while civil aviation dominated on distances over 1000 km, where its market share reached 93%. Although some empirical support exists, the vertical distinction between air-HSRs has yet to be comprehensively considered in theoretical investigations. To this end, a strategy of competition and collaboration between air-HSRs under vertical differentiation is first applied in this study.

Second, most theoretical research focuses on the airport-HSR company competition by a single parameter [5, 9, 15]. However, civil aviation and HSR compete for all kinds of passengers with different preferences. Baumeister and Leung [17] analyzed the feasibility of mutual substitution between civil aviation and non-HSR transport and claimed that in terms of travel times, HSR could remain competitive against air travel at distances up to 400 km. Therefore, this study attempts to propose an approach that would offer passengers flexible options in the high-speed transportation market, regardless of the civil aviation-HSR collaboration of competition behaviors.

Meng et al. [18] and Jiang and Zhang [13] claimed that demand functions were sensitive only to PTP and distance. Alternatively, Xia and Zhang (2016) applied their model to examine the advantages of air-HSR infrastructure, which predicted a zero-sum result where the increased revenue of one side implied losses on the other side. Alternatively, this study attempts to cover more influencing factors (namely five) in the elaborated model and, as a result, quantify various utilities for different categories of passengers.

2.2. Carbon Dioxide Emissions in Transportation. The impact of civil aviation and HSR on the environment is of growing concern, mainly due to the projected increase in demand for high-speed transportation. Some empirical evidence (e.g., [1, 19–21]) shows that airlines' per-seat air pollution and carbon emissions are higher than those of HSR. The market equilibrium of airline-HSR competition with extracted natural factors has been widely studied, e.g., by Behrens and Pels [22]; Dobruszkes [23]; Park and Ha [24]; from a game theory standpoint [25]; or an analytical viewpoint [9]. D'Alfonso et al. [15] discussed the implication of air-HSR competition on the environment and revealed that when the emission of HSR was more serious than civil aviation, the revenue gained by shifting air passengers to a cleaner mode failed to compensate for the pollution generated by the new traffic mode. Socorro and Viecens [16] demonstrated that integration only reduced civil aviation emissions when the hub airport capacity restriction was not fatal. Chen et al. [26] compared emissions in the scenario with and without HSR by assessing both modes of substitution and traffic generation effects and showed that as traffic diverted from road and air increased, the net emissions at the operation stage turned negative, offsetting emissions from infrastructure construction and vehicle manufacturing.

Among the current theoretical studies on the carbon emissions of transportation modes, the effects of replacing air travel with HSR have been the subject of an academic investigation on particular circuits. The key topic of argumentation was the estimate of pollution reduction that could be accomplished by replacing some short-haul flights with HSR services (e.g., [21, 27]). However, the impact on revenue or the loss of variable carbon prices as a result of adopting a new operational strategy had no practical relevance in these works. In this paper, we attempt to build an evolutionary game model to study the impact of civil aviation and HSR strategies on revenue when PTPs and CTPs are changed. The two operators' strategies simultaneously control the number of passengers and service frequencies. Civil aviation and HSR can also change the details of combined strategies.

2.3. Evolutionary Game Theory. In the study of high-speed transport systems and its stakeholders, most scholars are willing to use game theory to study the strategic choice behavior of their competitive or cooperative relationships (e.g., [3, 9, 28, 29]). Evolutionary game theory is a tool for studying the strategic behavior of individuals in large interactive and complex systems [30], which has not been widely used in the transportation area as well as the issue of carbon neutrality. Mou et al. [31] built a logit dynamics model of travelers' choice based on an evolutionary game to explore the dynamic adaptation of travelers' choice of HSR and air in the case of HSR speedup. Chen et al. [32] used an evolutionary game theory approach to assess the diffusion of different hydrogen technologies in the air transport mode, which can achieve the net zero CO_2 emission goal. Since the number of passengers in the high-speed transport market is infinite, the strategy selection of the main transport mode (i.e., competing and cooperating) can be regarded as a group evolutionary game problem [31]. Its selection mechanism is a strategy for obtaining higher payments in the current period and being selected by more participants in the next period [33]. In this paper, PTP and CTP are seen as two main factors affecting game players' returns and strategy choices. We hope to find an optimal combined strategy of civil aviation and HSR under reasonable PTPs and CTPs through an evolutionary game model. Civil aviation and HSR can gain more revenue, while, simultaneously, high-speed transportation can reduce carbon emissions and realize sustainable development.

2.4. Shortcomings of the Available Research

(1) To the best of our knowledge, no comprehensive analysis of the distributive impacts of carbon pricing strategies and revenues on high-speed transportation development has been presented, although Frondel and Schubert [34] outlined three alternative mechanisms to reallocate the revenues originating from carbon pricing. Quite topical would be an analytical study of the competitive and cooperative relations between civil aviation and HSR using evolutionary game theory, where airport or HSR companies facing several (competing or cooperating) alternatives could choose to maximize their utility or payoff [35]. Such a study would explain how different interactive decision-making behaviors reach the current stable state and help decision-makers design the best strategy.

(2) PTPs, travel speed, comfort, safety, and accessibility of civil aviation and HSR affect tourists' transportation mode choices related to their passenger flow ratio, revenue, and profit (Feng et al., 2021). However, only a few studies have analyzed the impact of their changes on the market share of civil aviation and HSR from a game model perspective.

(3) Under the carbon-neutral target, carbon pricing can also affect the profit of civil aviation and HSR, thus influencing their behavior to open routes and expand flights (Peihong et al., 2021). However, game model-based predictions of civil aviation-HSR interaction, considering carbon trading prices (CTPs), are quite scarce.

3. Cost and Revenue

The costs and revenues of civil aviation and HSR are mainly determined by their market shares. In this section, logit models are used to assess the preference of travel mode choice related to passenger flow of civil aviation and HSR [36]. Considering that passengers are rational travelers, they will choose civil aviation or HSR based on their utility functions related to some factors of PTPs, travel speed, comfort, safety, and accessibility, defined as follows:

$$U_{\mathrm{Ti}} = \lambda_{\mathrm{ip}}u_{\mathrm{ip}} + \lambda_{\mathrm{iv}}u_{\mathrm{iv}} + \lambda_{\mathrm{is}}u_{\mathrm{is}} + \lambda_{\mathrm{ia}}u_{\mathrm{ia}} + \lambda_{\mathrm{ic}}u_{\mathrm{ic}}, \quad (1)$$

where $i = 1$ or 2 correspond to the two transportation modes (civil aviation and HSR, respectively); λ_{ip} is the weight of the price of the passenger ticket; λ_{iv} is the weight for travel speed; λ_{is} is the weight for comfort; λ_{ia} is the weight for safety; λ_{ic} is the weight for accessibility; u_{ip} is the economic utility for transport mode i; u_{iv} is the speed utility for transport mode i; u_{is} is the comfort utility for transport mode i; and u_{ia} is the safety utility for transport mode i; u_{ic} is the accessibility utility for transport mode i.

The five-factor property utility values are normalized within the interval [0, 1], as will be shown in equations (2)–(6).

The utility of passenger tickets for civil aviation and HSR comes mainly from the price paid by passengers for travel and their savings in travel costs. The higher the travel price paid by passengers, the lower the utility and vice versa.

$$u_{\mathrm{ip}} = \frac{a_i}{p_i d} + \beta_i\left(p^e - p_i\right)d_i + \gamma_i, \quad (2)$$

where p_i is the unit transportation cost of transport mode i; p^e is the unit cost expected to be paid by the passenger of transport mode i; d_i is the traveling distance of transport mode i; a_i is the sensitivity factor for paying travel costs of transport mode i; β_i is the sensitivity factor for travelers to save on travel costs of transport mode i; and γ_i is the intercept term.

The speed utility of civil aviation and high-speed rail depends on the operating speed of the carrier. The shorter the travel time of passengers is, the higher the utility; the longer the travel time of passengers is, the lower the utility.

$$u_{\mathrm{iv}} = \frac{v_i}{d_i}\mu_i + \gamma_i, \quad (3)$$

where v_i is the running speed of the transport mode i; d_i is the traveling distance of the transport mode i; μ_i is the sensitivity factor for the travel time of the transport mode i; and γ_i is the intercept term.

The comfort utility of civil aviation and HSR can be measured by passengers' travel fatigue recovery time, and the fatigue level is related to the travel time. The shorter the fatigue recovery time is, the higher the utility; the longer the fatigue recovery time is, the lower the utility.

$$u_{\mathrm{is}} = \frac{H}{\left(1 + \varphi_i e^{-\rho d_i / v_i}\right)}\overline{T}, \quad (4)$$

where H is the maximum time for passengers to recover from fatigue after traveling; φ_i is the sensitivity factor for the comfort of transport mode i; ρ_i is the fatigue recovery time factor per unit of travel time of transport mode i; v_i is the running speed of transport mode i; d_i is the traveling distance of transport mode i; and $\overline{T}$ is the cost of time.

The safety utility of civil aviation and HSR is mainly the probability of passengers arriving safely at their destinations; the closer the probability is to 1, the higher the safety utility, and vice versa, the lower the safety utility.

$$u_{\mathrm{ia}} = a_i \xi_i, \quad (5)$$

where a_i is the probability of arriving safely at the destination and ξ_i is the sensitivity factor for secure transport mode i.

The accessibility utility of civil aviation and HSR is mainly reflected in the nontransit time of passengers throughout the travel process. The longer the nontransit time, the lower the utility value, and vice versa, the higher the utility value.

$$u_{\mathrm{ic}} = \frac{k_i}{c_i \overline{T}}, \quad (6)$$

where c_i is the non-in-transit time of transport mode i; k_i is the sensitivity factor for accessibility of transport mode i; and $\overline{T}$ is the cost of time.

The essence of the competition and cooperation between HSR and civil aviation is market share. The logit model is a practical approach to investigating the distribution of passengers in the high-speed transport market, so the market share model is shown in the following equation:

$$f_i = \frac{e^{U_{\mathrm{Ti}}}}{\sum_{i=1}^{n} e^{U_{\mathrm{Ti}}}}, \quad (7)$$

where n is assigned 2.

Based on the market share of the two transport modes, the frequency and income can be calculated, as shown in the following equations:

$$T_i = Q' \frac{f_i}{s_i}, \quad (8)$$

$$P_i = Q' f_i t_i, \quad (9)$$

where T_i is the operating frequency per day of transport mode i; P_i is the revenue of transport mode i; Q' is the total or additional passenger flow of transport mode i; s_i is the capacity of transport vehicle i; and t_i is the passenger ticket of transport mode i, f_i is the market share of transport mode i.

Following Yang and Zhang [9] and Ding et al. [36], we define the cost function of operators as shown in the following equation:

$$C_i = T_i d_i c_i, \quad (10)$$

where d_i is the traveling distance of transport mode i and c_i is the cost of transport mode per kilometer.

Assume that there are only two modes of transportation from one city to the destination of another city: civil aviation and HSR. To calculate costs comprehensively, this study has highlighted the importance of carbon emissions, particularly in activities related to competition and cooperation with different modes of transportation. Referring to Liu et al. [37], the price of carbon emissions has been calculated and seems to be part of the cost, as shown in the following equation:

$$P_{\mathrm{ci}} = T_i d_i p_{\mathrm{ci}}, \quad (11)$$

where p_{ci} is the unit price of carbon emissions per kilometer.

Additional passenger flow will be generated when civil aviation and HSR become cooperative under the same origination and definition, thus generating excess cost and income, as shown in the following equations:

$$C_T = \sum_{i=1}^{2} c_i d_i \frac{Q' f_i}{s_i}, \quad (12)$$

$$P_T = \sum_{i=1}^{2} t_i Q' f_i. \quad (13)$$

When civil aviation and HSR choose different strategies (competing or cooperating), their revenue will be distinct. To comprehend the equation, the competing strategy is defined as subscript 1, and the cooperating strategy is defined as subscript 2.

If both sides choose to compete simultaneously, the revenue can be shown in equation (14); if both sides are likely to cooperate simultaneously, the revenue can be displayed in equation (15); if both sides are apt to cooperate or compete relatively, the revenue can be calculated in equations (16) and (17).

$$P_{i11} = P_i - C_i - P_{\text{ci}}, \tag{14}$$

$$P_{i22} = P_i - C_i + t_i Q^{'} f_i - c_i d_i \frac{Q^{'} f_i}{s_i} - P_{\text{ci}}, \tag{15}$$

$$P_{i12} = P_i - C_i + P'_{T1} - C'_{T1} - P_{\text{ci}}, \tag{16}$$

$$P_{i21} = P_i - C_i + P'_{T2} - C'_{T2} - P_{\text{ci}}, \tag{17}$$

where P'_{Ti} is the revenue when the transport mode i chooses to cooperate unilaterally and C'_{Ti} is the cost when the transport mode i chooses to cooperate unilaterally.

4. Evolutionary Game Model

4.1. Assumptions. The paper claims that civil aviation or HSR has incomplete information about the game. They have the same set of strategies in the game: {competing, cooperating}. Each of them is bounded rationally and has a specified probability of choosing a possible behavior. It agrees with them changing their strategies or operating methods. Both sides have a mission to gain more additional revenue or total profit.

P_1 indicates the net income earned when civil aviation chooses a competing strategy. Meanwhile, P_2 indicates the net income earned by HSR, which chooses to compete with civil aviation. P_T and C_T indicate the total excess income and cost when both civil aviation and HSR agree to build a cooperative alliance, respectively. Because of the gap between the construction and management abilities of civil aviation and HSR on profits, a and b are introduced separately to represent the percentage of civil aviation in additional revenue and cost. The difference in operating patterns between the two subjects is found, P'_{T1} and C'_{T1} indicate the additional revenue and cost of civil aviation when it chooses to cooperate and HSR chooses to compete, respectively, and P'_{T2} and C'_{T2} are used to, respectively, denote the excess gain and cost to HSR when HSR chooses to cooperate, and civil aviation chooses to compete. $Q^{'}$ indicates the average daily passenger flow in high-speed transportation, and $\Delta Q^{'}$ indicates increased passenger flow when two subjects form a cooperative alliance. This research q indicates a credit fine.

Based on the above analysis, the definition of each parameter is shown in Table 1. The parameters are assumed to satisfy: $P_1, P_2, P_T, P'_{T1}, P'_{T2}, C_T, C'_{T1}, C'_{T2}, Q^{'}, \Delta Q^{'}, a, b, q > 0$.

4.2. Model and Analysis. The evolution of high-speed transport system can be seen as the result of the dynamic game between civil aviation and HSR. The aim of this paper was to study two players' procedures for the evolutionary game and derive optimal options for their total profits. We assume that civil aviation's probability for cooperating is x, while, for competing, it is $1 - x$. Similarly, HSR's probability is y for cooperating and $1 - y$ for competing.

When civil aviation and HSR adopt competing strategies, they will gain revenue and pay the cost and corresponding carbon price of each passenger. When civil aviation and HSR adopt a unilaterally or bilaterally cooperating strategy, it is likely that both parties in the game will obtain excess payoff originating from additional passenger flow. If both civil aviation and HSR choose the cooperating strategy, the increased passenger flow will be $\Delta Q^{'}$. In particular, when each chooses to cooperate unilaterally, the increased passenger flow changes into one-third of the original. Under this combined strategy, both civil aviation and HSR should pay for the extra costs and the extra carbon price associated with the extra passenger flow. If one of the sides breaks the cooperation alliance, the other side will obtain the fine as compensatory, which will be paid by the nonreputable party.

Using the definitions of required parameters in Section 4.1 and above analysis, the payoff matrix of civil aviation and HSR was constructed, as shown in Table 2.

Each player's expect revenue depends on his own choice of strategy and the distribution of others' choices of strategies. Based on Smith [38], we could calculate the expect profit of each game player through the payoff matrix.

The expected profit of civil aviation is defined as E_{m1} with the choice of cooperating strategy and E_{m2} with competing strategy. The average profit is defined as E_m. Civil aviation's expected revenue and average expected revenue are given as follows:

$$\begin{aligned} E_{m1} &= y\left[P_1 + aP_T - bC_T - \frac{\left(Q^{'} + \Delta Q^{'}\right) f_1 d_1 p_{c1}}{s_1}\right] + (1-y)\left[P_1 + P'_{T1} - C'_{T1} - \frac{\left(Q^{'} + \Delta Q^{'}/3\right) f_1 d_1 p_{c1}}{s_1} + q\right] \\ &= P_1 + y\left(aP_T - bC_T\right) + (1-y)\left(P'_{T1} - C'_{T1} + q\right) - \left[Q^{'} + \frac{(1+2y)\Delta Q^{'}}{3}\right]\frac{f_1 d_1 p_{c1}}{s_1}, \\ E_{m2} &= y\left(P_1 - \frac{Q^{'} f_1 d_1 p_{c1}}{s_1} - q\right) + (1-y)\left(P_1 - \frac{Q^{'} f_1 d_1 p_{c1}}{s_1}\right) = P_1 - \frac{Q^{'} f_1 d_1 p_{c1}}{s_1} - yq, \\ E_m &= xE_{m1} + (1-x)E_{m2}. \end{aligned} \tag{18}$$

Table 1: Definitions of model parameters.

Parameters	Definitions
P_1	Income of civil aviation that chooses unilaterally competing strategy
P_2	Income of HSR that chooses unilaterally competing strategy
P_T	Total excess income of cooperation between civil aviation and HSR
P'_{T1}	Excess income of civil aviation that chooses unilaterally cooperating strategy
P'_{T2}	Excess income of civil aviation that chooses unilaterally cooperating strategy
C_T	Total excess cost of cooperation between civil aviation and HSR
C'_{T1}	Excess cost of civil aviation that chooses unilaterally cooperating strategy
C'_{T2}	Excess cost of civil aviation that chooses unilaterally cooperating strategy
Q'	Average daily passenger flow in high-speed transportation
$\Delta Q'$	Increased passenger flow
a	Percentage of civil aviation in total excess income
b	Percentage of civil aviation in total excess income
q	Credit fine

With the exploration of evolutionary game theory, the definition "replicator dynamic" is mentioned by Sandholm [39] so that civil aviation's dynamic equation of replication takes the following form:

$$F(x) = \frac{\mathrm{d}x}{\mathrm{d}t} = x\left(E_{m1} - E_m\right) = x(1-x)\left\{ y\left(aP_T - bC_T\right) + (1-y)\left(P'_{T1} - C'_{T1}\right) - \frac{(1+2y)\Delta Q'}{3}\frac{f_1 d_1 p_{c1}}{s_1} + q \right\}. \tag{19}$$

Therefore, the expected profit is defined as E_{n1} when HSR is apt to cooperate and E_{n2} when HSR focuses on competing. The average profit is defined as E_n. The HSR's expected revenue and average revenue are calculated via the following equations:

$$\begin{aligned} E_{n1} &= x\left[P_2 + (1-a)P_T - (1-b)C_T - \frac{\left(Q' + \Delta Q'\right) f_2 d_2 p_{c2}}{s_2}\right] + (1-x)\left[P_2 + P'_{T2} - C'_{T2} - \frac{\left(Q' + \Delta Q'/3\right) f_2 d_2 p_{c2}}{s_2} + q\right] \\ &= P_2 + x\left[(1-a)P_T - (1-b)C_T\right] + (1-x)\left(P'_{T2} - C'_{T2} + q\right) - \left[Q' + \frac{(1+2x)\Delta Q'}{3}\right]\frac{f_2 d_2 p_{c2}}{s_2}, \end{aligned} \tag{20}$$

$$E_{n2} = x\left[P_1 + P'_{T1} - C'_{T1} - \frac{\left(Q' + \Delta Q'/3\right) f_1 d_1 p_{c1}}{s_1} + q\right] + (1-x)\left(P_1 - \frac{Q' f_1 d_1 p_{c1}}{s_1}\right) = P_2 - \frac{Q' f_2 d_2 p_{c2}}{s_2} - xq, \tag{21}$$

$$E_n = yE_{n1} + (1-y)E_{n2}. \tag{22}$$

Simultaneously, the replication dynamic equation for HSR can be presented as follows:

$$G(y) = \frac{\mathrm{d}y}{\mathrm{d}t} = y\left(E_{n1} - E_n\right) = y(1-y)\left\{ x\left[(1-a)P_T - (1-b)C_T\right] + (1-x)\left(P'_{T2} - C'_{T2}\right) - \frac{(1+2x)\Delta Q'}{3}\frac{f_2 d_2 p_{c2}}{s_2} + q \right\}. \tag{23}$$

Table 2: Payoff matrix for civil aviation and HSR.

		HSR	
		Cooperating (y)	Competing $(1-y)$
Civil aviation	Cooperating (x)	$P_1 + aP_T - bC_T - (Q^{'}+\Delta Q^{'}) f_1 d_1 p_{c1}/s_1$, $P_2 + (1-a)P_T - (1-b)C_T - (Q^{'}+\Delta Q^{'}) f_2 d_2 p_{c2}/s_2$	$P_1 + P_{T1}' - C_{T1}' - (Q^{'}+\Delta Q^{'}/3) f_1 d_1 p_{c1}/s_1 + q$, $P_2 - Q^{'} f_2 d_2 p_{c2}/s_2 - q$
	Competing $(1-x)$	$P_1 - Q^{'} f_1 d_1 p_{c1}/s_1 - q$, $P_2 + P_{T2}' - C_{T2}' - (Q^{'}+\Delta Q^{'}/3) f_2 d_2 p_{c2}/s_2 + q$	$P_1 - Q^{'} f_1 d_1 p_{c1}/s_1$, $P_2 - Q^{'} f_2 d_2 p_{c2}/s_2 - xq$

A two-dimensional dynamical system for the evolutionary game between civil aviation and HSR takes the following form:

$$\begin{cases} \dfrac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)\left\{ y(aP_T - bC_T) + (1-y)(P'_{T1} - C'_{T1}) - \dfrac{(1+2y)\Delta Q'}{3M} + q \right\}, \\ \dfrac{\mathrm{d}y}{\mathrm{d}t} = y(1-y)\left\{ x[(1-a)P_T - (1-b)C_T] + (1-x)(P'_{T2} - C'_{T2}) - \dfrac{(1+2x)\Delta Q'}{3N} + q \right\}, \end{cases} \tag{24}$$

where M and N are the unit carbon prices of civil aviation and HSR, respectively.

5. Evolutionary Stability Analysis

5.1. Stability Analysis of the Equilibrium Points. Equating the above civil aviation and HSR formulas to zero, all possible equilibrium points were calculated. Given the stability conditions of the differential equation, five partial equilibrium points of government policy and social network platform strategy selection were derived as follows: $E_1(0,0)$, $E_2(0,1)$, $E_3(1,0)$, $E_4(1,1)$, and $E_5(x^*, y^*)$.

Weibull [40] and Friedman [41] proposed that not all equilibrium points should be treated as stable points. Therefore, we calculated the stability of each point via the Jacobian matrix as follows:

$$J = \begin{bmatrix} \dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y} \\ \dfrac{\partial G(y)}{\partial x} & \dfrac{\partial G(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} \delta_1 & \delta_2 \\ \delta_3 & \delta_4 \end{bmatrix}. \tag{25}$$

Combining (19) and (20) yields:

$$\begin{aligned} \delta_1 &= (1-2x)\left\{ y(aP_T - bC_T) + (1-y)(P'_{T1} - C'_{T1}) - \frac{(1+2y)\Delta Q'}{3M} + q \right\}, \\ \delta_2 &= x(1-x)\left(aP_T - bC_T - P'_{T1} + C'_{T1} - \frac{2\Delta Q'}{3M} \right), \\ \delta_3 &= y(1-y)\left[(1-a)P_T - (1-b)C_T - P'_{T2} + C'_{T2} - \frac{2\Delta Q'}{3N} \right], \\ \delta_4 &= (1-2y)\left\{ x[(1-a)P_T - (1-b)C_T] + (1-x)(P'_{T2} - C'_{T2}) - \frac{(1+2x)\Delta Q'}{3N} + q \right\}. \end{aligned} \tag{26}$$

5.2. Evolutionary Stability in Different Scenarios. According to Friedman [41], if the matrix rank exceeds zero, while the matrix trace is less than zero, a combination of mixed tactics will become a stable strategic equilibrium. The traces of five equilibrium points listed in Table 3 were used to get the stability results for different cases as shown in Table 4.

The evolutionary phase diagrams for each scenario are shown in Figures 1–6. These diagrams have arrows pointing along the final direction under each set of circumstances. In scenarios 3 to 6, only one ESS figures in the system; hence, the final evolutionary trend is distinct. Scenarios 1 and 2 have two ESSs. Six scenarios can be developed by considering the trends in the strategies that civil aviation and HSR adopt during the system's evolutionary process.

5.2.1. Scenario 1. Figure 1 depicts the dynamic evolutionary track of scenario 1. When $aP_T > bC_T$, $(1-a)P_T > (1-b)C_T$, $P'_{T1} < C'_{T1}$ and $P'_{T2} < C'_{T2}$, the stable points of the system are (0, 0) and (1, 1). In this case, civil aviation and HSR choose the same strategy, and both will earn more additional profit. If both sides choose cooperative behavior

Table 3: The trace of five equilibrium points.

Equilibrium point	Det (J)	Tr (J)
$E_1\,(0,0)$	$(P'_{T1}-C'_{T1}+q-\Delta Q' M/3)(P'_{T2}-C'_{T2}-\Delta Q' N/3+q)$	$P'_{T1}-C'_{T1}+P'_{T2}-C'_{T2}+2q-\Delta Q' M/3-\Delta Q' N/3$
$E_2\,(0,1)$	$(C'_{T2}-P'_{T2}+\Delta Q' N/3-q)(aP_T-bC_T-\Delta Q' M+q)$	$aP_T-bC_T-P'_{T2}+C'_{T2}-\Delta Q' M+\Delta Q' N/3$
$E_3\,(1,0)$	$(C'_{T1}-P'_{T1}+\Delta Q' M/3-q)[(1-a)P_T-(1-b)C_T-\Delta Q' N+q]$	$C'_{T1}-P'_{T1}+(1-a)P_T-(1-b)C_T+\Delta Q' M/3-\Delta Q' N$
$E_4\,(1,1)$	$(bC_T-aP_T+\Delta Q' M-q)[(1-b)C_T-(1-a)P_T+\Delta Q' N-q]$	$C_T-P_T+\Delta Q' M+\Delta Q' N-2q$
$E_5\,(x^*,y^*)$	$\lambda_1 * \lambda_2$	—

Note. $x^*=(3P_{T2}-3C_{T2}+3q-\Delta Q' N)/[3(1-a)P_T+3(1-b)C_T+3P_{T2}-3C_{T2}+2\Delta Q' N]$ $y^*=(3C_{T1}-3P_{T1}-\Delta Q' M+3q)/(3P_{T1}-3C_{T1}+3bC_T-3aP_T+2\Delta Q' M)$.

Table 4: Stability of the equilibrium point in different scenarios.

No	Scenario	ESS
0	$aP_T<bC_T,\ (1-a)P_T>(1-b)C_T,\ P'_{T1}>C'_{T1},\ P'_{T2}<C'_{T2}$ $aP_T>bC_T,\ (1-a)P_T<(1-b)C_T,\ P'_{T1}<C'_{T1},\ P'_{T2}>C'_{T2}$	No ESS exists
1	$aP_T>bC_T\,(1-a)P_T>(1-b)C_T,\ P'_{T1}<C'_{T1},\ P'_{T2}<C'_{T2}$	$(0,0),\ (1,1)$
2	$aP_T<bC_T,\ (1-a)P_T<(1-b)C_T,\ P'_{T1}>C'_{T1},\ P'_{T2}>C'_{T2}$	$(0,1),\ (1,0)$
3	$aP_T<bC_T,\ (1-a)P_T<(1-b)C_T,\ P'_{T1}<C'_{T1},\ P'_{T2}<C'_{T2}$ $aP_T<bC_T,\ (1-a)P_T>(1-b)C_T,\ P'_{T1}<C'_{T1},\ P'_{T2}<C'_{T2}$ $aP_T>bC_T,\ (1-a)P_T<(1-b)C_T,\ P'_{T1}<C'_{T1},\ P'_{T2}<C'_{T2}$	$(0,0)$
4	$aP_T<bC_T,\ (1-a)P_T<(1-b)C_T,\ P'_{T1}<C'_{T1},\ P'_{T2}>C'_{T2}$ $aP_T<bC_T,\ (1-a)P_T>(1-b)C_T,\ P'_{T1}>C'_{T1},\ P'_{T2}>C'_{T2}$ $aP_T<bC_T,\ (1-a)P_T>(1-b)C_T,\ P'_{T1}<C'_{T1},\ P'_{T2}>C'_{T2}$	$(0,1)$
5	$aP_T<bC_T,\ (1-a)P_T<(1-b)C_T,\ P'_{T1}>C'_{T1},\ P'_{T2}<C'_{T2}$ $aP_T>bC_T,\ (1-a)P_T<(1-b)C_T,\ P'_{T1}>C'_{T1},\ P'_{T2}>C'_{T2}$ $aP_T>bC_T,\ (1-a)P_T<(1-b)C_T,\ P'_{T1}>C'_{T1},\ P'_{T2}<C'_{T2}$	$(1,0)$
6	$aP_T>bC_T,\ (1-a)P_T>(1-b)C_T,\ P'_{T1}>C'_{T1},\ P'_{T2}>C'_{T2}$ $aP_T>bC_T,\ (1-a)P_T>(1-b)C_T,\ P'_{T1}>C'_{T1},\ P'_{T2}<C'_{T2}$ $aP_T>bC_T,\ (1-a)P_T>(1-b)C_T,\ P'_{T1}<C'_{T1},\ P'_{T2}>C'_{T2}$	$(1,1)$

simultaneously, the excess revenue generated by increased traffic is higher than the excess cost; if both sides choose competitive behavior simultaneously, civil aviation and HSR will take advantage of gaining more market share. This strategic combination of civil aviation and HSR is (competing, competing) and (cooperating, cooperating).

5.2.2. Scenario 2. Figure 2 depicts the dynamic evolutionary track of scenario 2. When $aP_T<bC_T$, $(1-a)P_T<(1-b)C_T$, $P'_{T1}>C'_{T1}$, and $P'_{T2}>C'_{T2}$, the stable points of the system are (0, 1) and (1, 0). At this point, civil aviation and HSR choose different strategies. The increase in the traffic flow from cooperative behavior cannot bring the desired excess revenue to both sides, and the revenue gained from competitive behavior is not enough to offset the costs and penalties. This strategic combination of civil aviation and HSR is (competing, cooperating) and (cooperating, competing).

5.2.3. Scenario 3. Figure 3 depicts the dynamic evolutionary track of scenario 3. When $P'_{T1}<C'_{T1}$ and $P'_{T2}<C'_{T2}$, the stable point is (0, 0). In this case, civil aviation and HSR choose to compete. Whether civil aviation or HSR chooses to cooperate jointly or unilaterally, the expected benefits will not offset the costs. Therefore, in this scenario, the system will gradually converge to the trend of competition; that is, the strategic combination of civil aviation and HSR is (competing, competing).

5.2.4. Scenario 4. Figure 4 depicts the dynamic evolutionary track of scenario 4. When $aP_T<bC_T$ and $P'_{T2}>C'_{T2}$, the stable point of the system is (0,1). At this point, civil aviation chooses to compete, and HSR chooses to cooperate. Civil aviation chooses unilateral competitive behavior that obtains benefits in excess of costs and penalties, while HSR chooses unilateral cooperative behavior that also increases additional passenger traffic flow and generates excess benefits above excess costs. This strategic combination of civil aviation and HSR is (competing, cooperating).

5.2.5. Scenario 5. Figure 5 depicts the dynamic evolutionary track of scenario 5. When $(1-a)P_T<(1-b)C_T$ and $P'_{T1}>C'_{T1}$, the stable point is (1,0). At this point, civil aviation chooses to cooperate, and HSR chooses to compete. While civil aviation chooses unilateral cooperative behavior that increases additional passenger traffic flow and gains excess revenue over excess costs, HSR chooses unilateral competitive behavior that captures revenue in excess of costs and penalties. This strategic combination of civil aviation and HSR is (cooperating, competing).

5.2.6. Scenario 6. Figure 6 depicts the dynamic evolutionary track of scenario 6. When $aP_T>bC_T$ and $(1-a)P_T>(1-b)C_T$, the stable point of the system is (1, 1). In this case, civil aviation and HSR choose to cooperate. There will be severe losses in high-speed transport systems

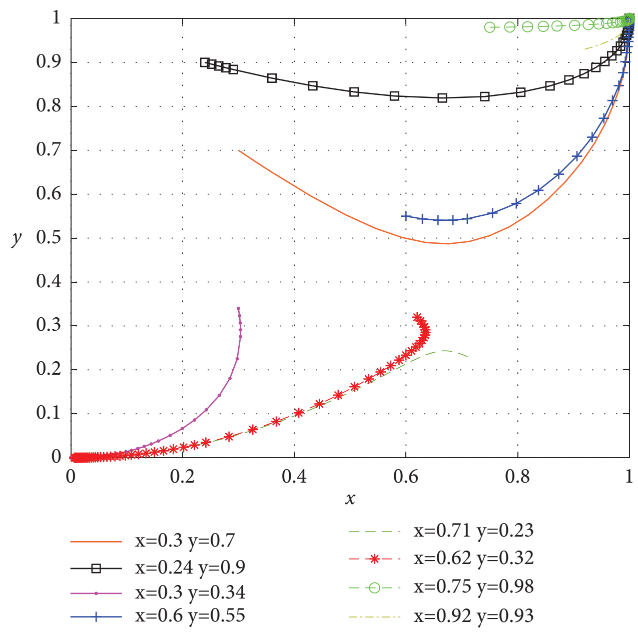

Figure 1: Evolutionary path diagram of scenario 1.

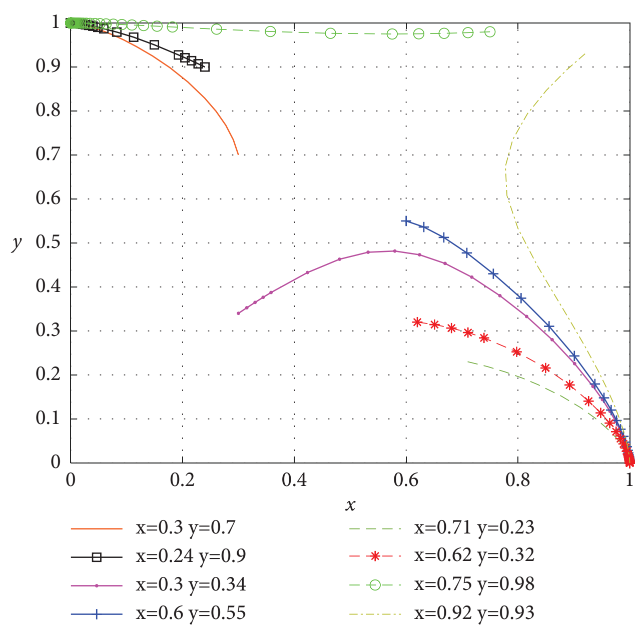

Figure 2: Evolutionary path diagram of scenario 2.

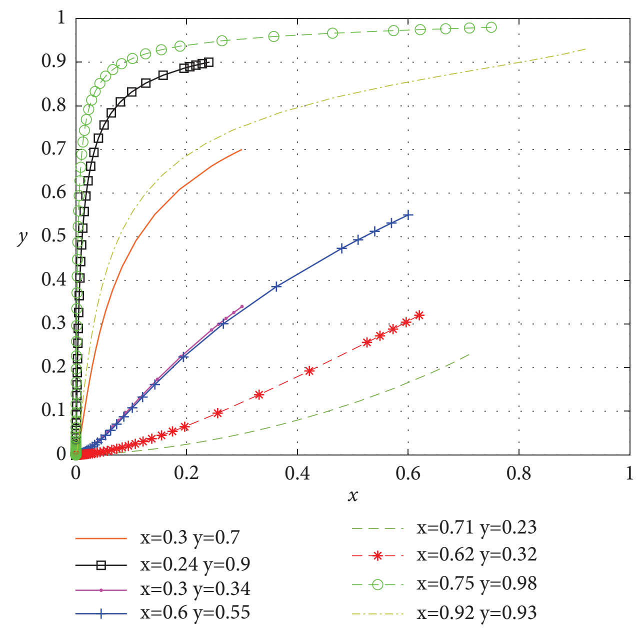

Figure 3: Evolutionary path diagram of scenario 3.

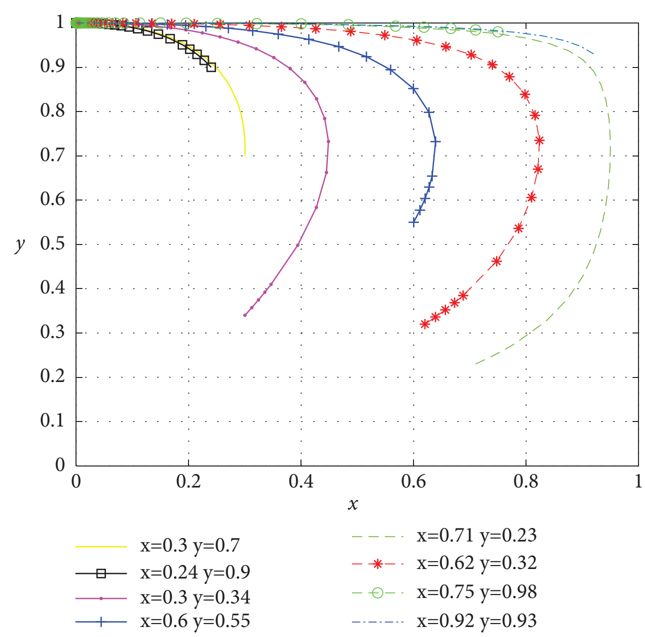

Figure 4: Evolutionary path diagram of scenario 4.

under the conflict between them. The increased traffic flow generates excess revenue, and since it is higher than the excess cost, both sides will be profitable. This strategic combination of civil aviation and HSR is (cooperating, cooperating).

Based on the above six cases, the effects on the increased traffic flow's initial probability and excess revenue were analyzed and discussed in Section 6. In practice, the manufacturer can benefit directly from the increased traffic flow when civil aviation and HSR cooperate. Therefore, only the excess revenue will be discussed in detail in the following sections.

6. Case Study Analysis and Discussion

6.1. A Case Study of Beijing–Shanghai Corridor Based on Six Combined Strategies. Civil aviation will probably predominate in medium- and long-distance sectors before HSR enters the market. The Beijing–Shanghai HSR route (analyzed here as a case study) has 24 stations with a total length of 1318 km and a maximum designed speed of 380 km/h. In contrast to a nearly two-hour flight between the two cities, the fastest HSR service between Shanghai and Beijing takes about 4 h at a cheaper ticket price. HSR is quite competitive

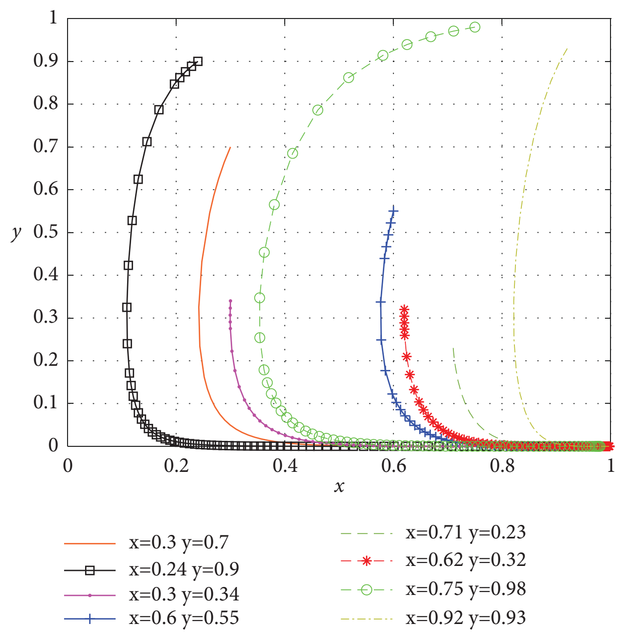

Figure 5: Evolutionary path diagram of scenario 5.

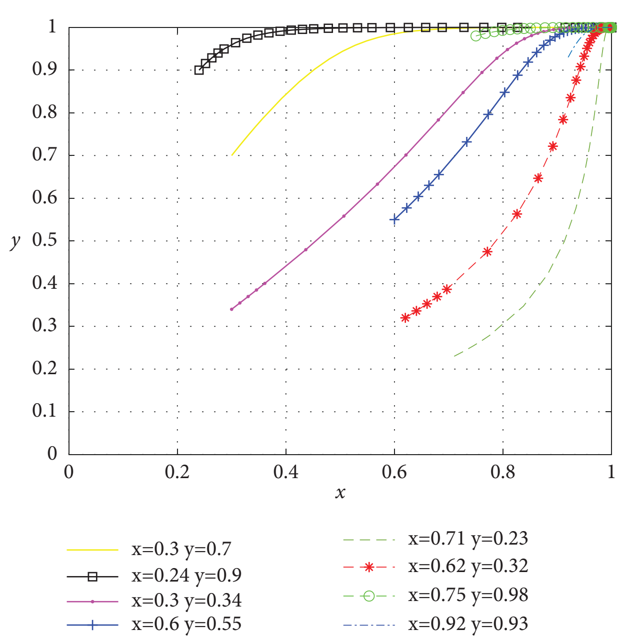

Figure 6: Evolutionary path diagram of scenario 6.

in this long-haul route, taking prolonged check-in and boarding procedures for a flight into account. In the Beijing–Shanghai corridor analysis, a daily passenger flow of 450,000 people is assumed. We design five combination strategies based on PTPs and CTPs to verify the validity of this study to compare and analyze the impact of variable PTPs under constant CTPs and variable CTPs at constant PTPs on the evolutionary game behavior of civil aviation and HSR. The mileage of civil aviation is approximately 1178 km, assuming that the airline company assigns a B737 to fly; the mileage of HSR way is approximately 1318 km, assuming that the HSR company uses CR400AF high-speed trains. The parameters of the six strategies associated with the Beijing–Shanghai corridor were derived from statistical data from Luo et al. [10] and Gao et al. [42], as shown in Table 5.

Figure 7 shows the levels of equilibrium revenue and the trend of the variable CTPs of civil aviation and HSR in the six different combined strategies in the Beijing–Shanghai corridor (additional data on the combined strategies are provided in Table 6). For aviation, there is an increase in civil aviation passengers' market share of 1% and a decrease in HSR passengers' market share of 1% by growth in PTPs. To observe the variation in cost and revenue, we increased the aviation PTP to 112 USD and the HSR PTP to 140 USD. Meanwhile, we increased the respective CTPs to 6.6 and 14 USD. With the increased CTPs, the equilibrium revenue dropped from −546700 USD in strategy 1 to −781200 USD in strategy 3 for civil aviation and from 561700 USD in strategy 4 to 475800 USD in strategy 6 for HSR. It can be observed that the revenue will be lower for higher CTPs. In conclusion, higher PTPs and CTPs will facilitate cooperative alliances and maximize the benefits of both sides.

6.2. Key Simulation on Evolutionary Game and Results. Huberman and Glance [43] presented that in an evolutionary game where player interactions depend upon delayed information, a simulation may still possess many complicated dynamical features. This study applied Beijing–Shanghai HSR route to display two game players' dynamic strategy setting. We assumed that the initial probability of each of the two subjects was 0.5, and airport and HSR companies were inclined to collaborate. The initial willingness values of each subject (x and y) were plotted along the vertical axis of the diagrams constructed in this section. The initial willingness ranged from 0 to 1, with the horizontal axis representing the time progression.

Based on ESS points, we assessed key parameters' impact on the evolutionary game's outcomes. When analyzing a parameter's sensitivity to the evolutionary game's outcome, we assumed that the remaining parameters' values did not change. Based on the data in Table 4, initial simulation parameter values of six combined strategies can be calculated and provided in Table 7. Three values of the additional revenue (P_T) were used (namely, 700KUSD, 1200KUSD, and 1400KUSD), while other parameters remained unchanged in six combined strategies.

For the initial P_T values of 700KUSD, 1200KUSD, and 1400KUSD, the simulation results of combined strategy 1 were obtained and plotted in Figure 8. As seen in Figure 8, at $P_T = 700$KUSD and $P_T = 1200$KUSD, the x and y values continue decreasing and tend to 0, demonstrating that in the initial stage, the insufficient benefit cannot promote air and HSR to cooperate. At $P_T = 1400$KUSD, x and y increase, finally approaching 1 and indicating that sufficient benefit can rapidly accelerate the establishment of an air-HSR alliance under the limited probabilities of choices. Two subjects will become more willing to implement the cooperative strategy. It can be concluded that the benefits due to lower PTPs and CTPs have an important role in promoting partnerships and actively motivating air-rail transportation.

Table 5: The parameters of six strategies.

Strategy		PTP (USD)	Capacity (person)	CO_2 emission (t/km)	CTP (USD)	Speed (km/h)	Safety	Comfort	Accessibility
1	Air	71.8	232	0.21	6.6	900	0.999	0.95	0.003
	HSR	47.6	576	0.24	6.6	350	0.998	0.88	0.0092
2	Air	112	232	0.21	11.2	900	0.999	0.95	0.003
	HSR	84	576	0.24	11.2	350	0.998	0.88	0.0092
3	Air	71.8	232	0.21	14	900	0.999	0.95	0.003
	HSR	46.6	576	0.24	14	350	0.998	0.88	0.0092
4	Air	112	232	0.21	6.6	900	0.999	0.95	0.003
	HSR	84	576	0.24	6.6	350	0.998	0.88	0.0092
5	Air	154	232	0.21	11.1	900	0.999	0.95	0.003
	HSR	47.6	576	0.24	11.2	350	0.998	0.88	0.0092
6	Air	112	232	0.21	14	900	0.999	0.95	0.003
	HSR	84	576	0.24	14	350	0.998	0.88	0.0092

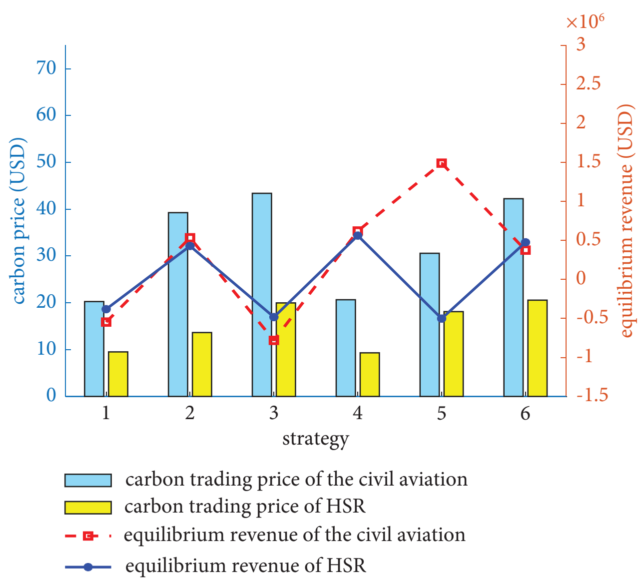

Figure 7: The price variation in the six strategies.

Table 6: Six combined strategies for evolutionary game.

Strategy		Frequency	Fi (%)	Cost (USD)	Income (USD)	(x^*, y^*)
1	Air	101	52.30	2409904	−546700	(0.25, 0.89)
	HSR	37	47.70	1534834	−381200	
2	Air	115	59.70	2750902	534000	(0.16, 0.15)
	HSR	32	40.30	1296722	428600	
3	Air	102	52.80	2432948	−781200	(0.28, 0.74)
	HSR	36	47.20	1518734	−482800	
4	Air	103	53.30	2455992	620700	(0.29, 0.84)
	HSR	37	46.70	1502648	561700	
5	Air	90	46.50	2142938	1490100	(0.28, 0.99)
	HSR	41	53.50	1721454	−502000	
6	Air	99	51.40	2368450	375400	(0.17, 0.64)
	HSR	38	48.60	1562680	475800	

Table 7: Initial parameter values of six combined strategies for evolutionary game.

Strategy	C_T (KUSD)	a (KUSD)	b (KUSD)	R_1 (KUSD)	R_2 (KUSD)	C_1 (KUSD)	C_2 (KUSD)	M (USD)	N (USD)	q (KUSD)
1	710	0.62	0.61	110	160	130	80	0.36	0.17	70
2	730	0.66	0.67	200	100	150	70	0.71	0.24	70
3	710	0.62	0.61	110	180	130	80	0.78	0.36	70
4	710	0.60	0.62	170	360	130	80	0.37	0.16	70
5	700	0.73	0.55	210	−70	110	90	0.55	0.32	70
6	710	0.58	0.60	170	220	120	270	0.76	0.37	70

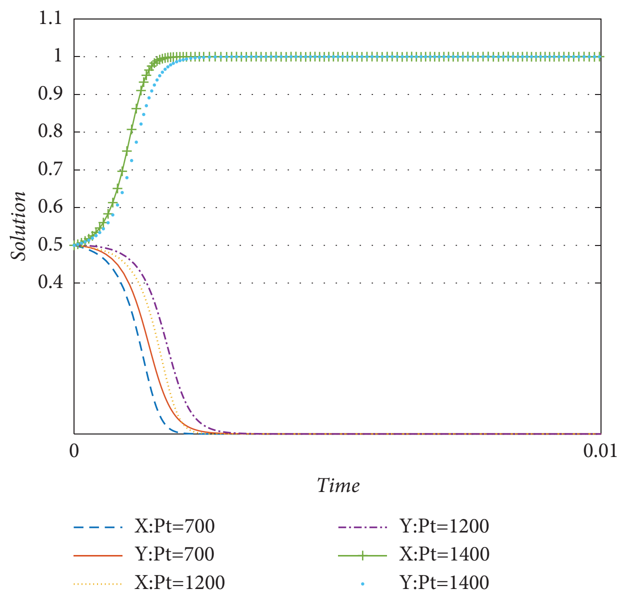

Figure 8: The simulation results of combined strategy 1.

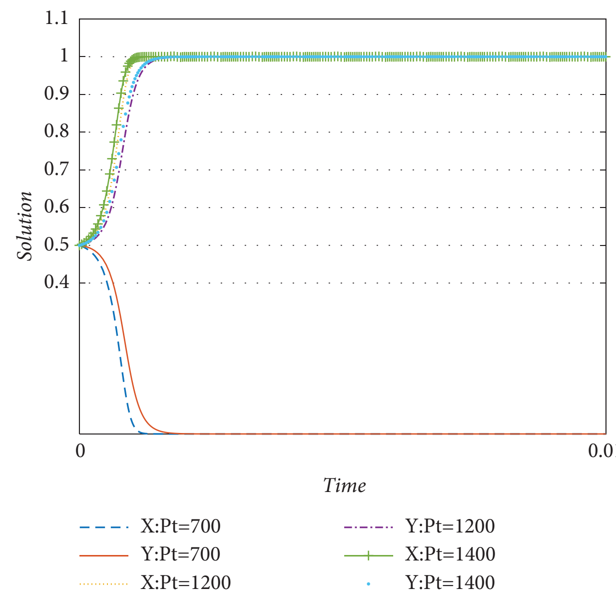

Figure 9: The simulation results of combined strategy 2.

For the initial values of $P_T = 700$KUSD, $P_T = 1200$KUSD, and $P_T = 1400$KUSD, the simulation result of combined strategy 2 is shown in Figure 9. As seen in Figure 9, at $P_T = 700$KUSD, x and y values always decrease and eventually stabilize at 0. At $P_T = 1200$KUSD and $P_T = 1400$KUSD, x and y increase, finally approaching 1, demonstrating that some additional revenue can initially inspire civil aviation's and HSR's willingness for the alliance, but it will increase the motivation to build a cooperative alliance and then gradually increase the willingness to implement the synergistic measures. Combined with Figure 8, it shows that a certain range of increases in passenger tickets and carbon prices and additional revenue will accelerate the initiative of civil aviation and choose a collaborative strategy, which will increase total profit.

For the initial P_T values of 700KUSD, 1200KUSD, and 1400KUSD, the simulation results of combined strategy 3 were obtained and plotted in Figure 10, which indicates that the x and y values always continue to increase and stabilize at 1. As P_T increases, x and y grow more quickly, implying that lower PTPs can strongly promote the cooperation union. Still, the CTP designed by the government needs to develop to an extremely high level. In contrast to Figure 8, it implies that with the CTP growth under lower PTPs, the airline and HSR companies will withdraw from competing strongly and have the incentive to cooperate with the connecting customers in the transport market.

For the initial P_T values of 700KUSD, 1200KUSD, and 1400KUSD, the simulation results of combined strategy 4 were obtained and plotted in Figure 11, which results are similar to those of Figure 10. The trend of the evolutionary game in strategy 4 indicates that civil aviation and HSR are willing to choose the cooperating strategy. According to Figure 9, we can conclude that at $P_T = 70$KUSD, civil aviation and HSR will choose a competing strategy with HSR and charge a higher CTP, leading to increased passenger flow compared to the cooperation strategy. According to Figure 8, at $P_T = 70$KUSD and $P_T = 120$KUSD, civil aviation is apt to compete with HSR and charge a lower PTP, which will earn huge profit by making the cooperative decision.

With the initial values of $P_T = 700$KUSD, $P_T = 1200$KUSD, and $P_T = 140$KUSD, the simulation results of combined strategy 5 are shown in Figure 12, which results are similar to those of Figure 9. This indicates that with the growth of PTPs, civil aviation is marginally more vulnerable to additional revenue than HSR. Along with the airline's PTP growth and the HSR PTP decline, two objects are marginally more sensitive to change strategies under medium carbon prices.

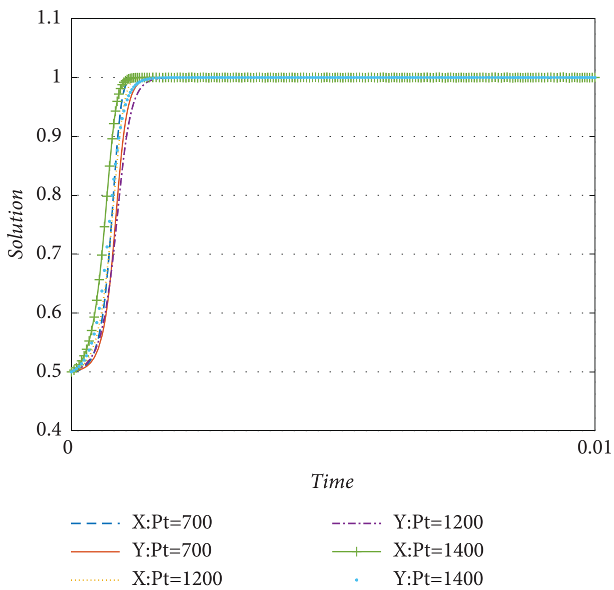

Figure 10: The simulation results of combined strategy 3.

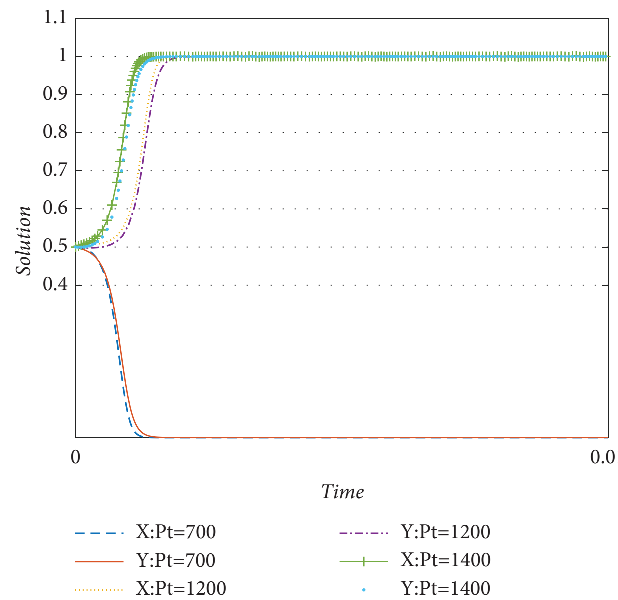

Figure 12: The simulation results of combined strategy 5.

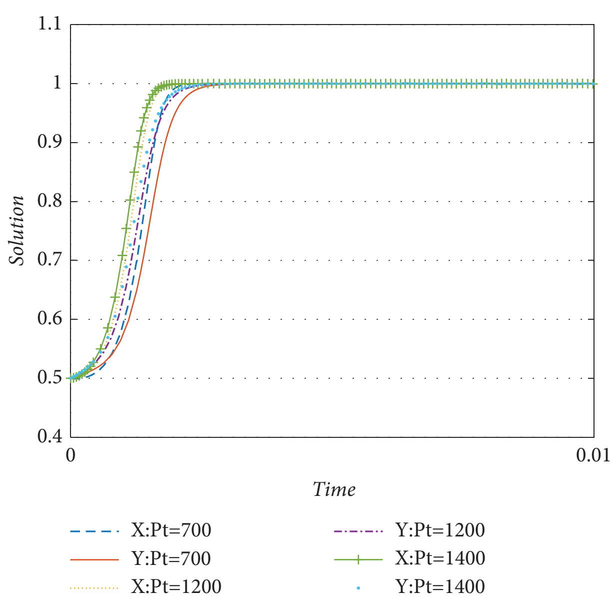

Figure 11: The simulation results of combined strategy 4.

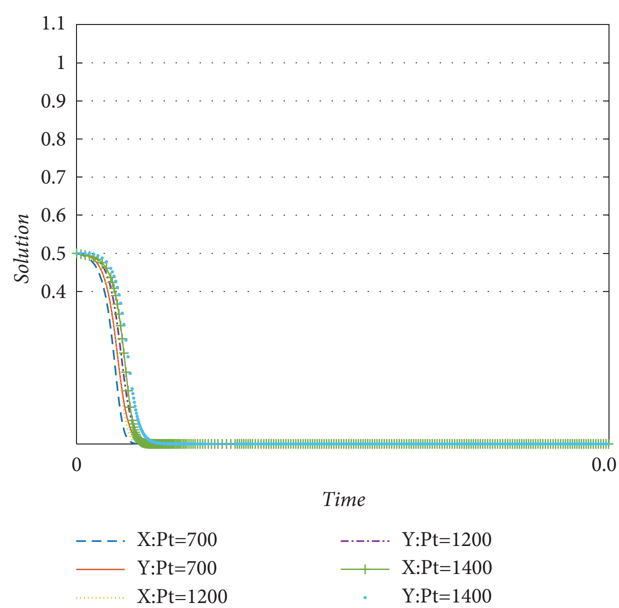

Figure 13: The simulation results of combined strategy 6.

For the initial values of $P_T = 700$KUSD, $P_T = 1200$KUSD, and $P_T = 1400$KUSD, the simulation results of combined strategy 6 are shown in Figure 13, which indicates that the values of x and y keep dropping, eventually reaching zero. This may be because civil aviation and HSR are dominated by competing strategies, which incur lower costs and earn greater profits, and the airport must maintain a competitive edge. The comparative analysis of Figures 11 and 13 implies that the huge growth of HSR PTPs and CTPs cannot strongly change the competing decision made by two subjects; civil aviation's and HSR's trends both approach zero at excessive CPT values.

7. Conclusions

Based on the logit method, this study elaborated a two-dimensional evolutionary game model to reveal the competition and cooperation between high-speed rail (HSR) and civil aviation companies. Travel time, passenger ticket prices (PTPs), and carbon trading prices (CTPs) were considered in this model to obtain the passenger flow ratios, revenues, and profits of HSR and civil aviation. Furthermore, the evolutionarily stable strategy solutions of the game model were obtained and discussed under different variable conditions. Finally, the Beijing–Shanghai corridor was used as a case study in the strategy simulations to validate the proposed model's feasibility.

The main findings are as follows:

(1) Based on evolutionary game stability theory analysis, two equilibrium points $E_1(0,0)$ and $E_4(1,1)$ corresponded to stability strategies under specific conditions ($aP_T < bC_T$, $(1-a)P_T > (1-b)C_T$, $P'_{T1} < C'_{T1}$, $P'_{T2} < C'_{T2}$ and $aP_T > bC_T$ $(1-a)P_T > (1-b)C_T$, $P'_{T1} < C'_{T1}$, $P'_{T2} > C'_{T2}$), implying that two civil aviation and HSR companies will decide to compete or cooperate synchronously in various combined strategies. China's HSR market still needs to develop, and there remains a gap in the optimal profit of each transport mode. To improve the application efficiency of transportation resources, civil aviation and HSR should keep the market in balance, first through a pricing mechanism to maintain the high standard of PTPs and then with guidance and encouragement by the government to reduce CTPs.

(2) The final behavior of civil aviation and HSR companies is affected by the growth rate of additional revenue. The greater the additional revenue to the collaborative strategy, the higher civil aviation's initiative to promote the establishment of alliance, and the readiness of civil aviation and HSR companies to make cooperative choices that maximize total profit. In order to maintain the growth rate of additional revenue, airports and rail companies should adopt targeted measures to serve different types of passengers and expand passenger demand more efficiently based on the alliance.

(3) The PTP and CTP values control the strategic choice of each gaming subject and terminally determine whether the high-speed transportation market can be effectively operated. Among them, an appropriate increase under the same CTP level can promote each subject's strategic choice to the ideal decision direction (cooperating, cooperating). Meanwhile, when keeping PTPs unchanged, with the huge growth of CTPs, civil aviation and HSR are likely to choose competing strategies, and the additional revenue from cooperation would not attract them to change their competitive behaviors. Therefore, it is necessary for the airport and HSR companies to coordinate the PTP and CTP strategies, ensuring that they float up and down at reasonable intervals, thus ensuring optimal revenue distribution in the high-speed transportation market [44].

Data Availability

Some or all data, models, or codes generated or used during the study are available from the corresponding author upon request.

Conflicts of Interest

All authors declare that they have no conflicts of interest.

Authors' Contributions

Bo Sun and Ming Wei conceptualized the manuscript; Ming Wei developed the methodology; Zehui Xu performed the formal analysis; Zehui Xu wrote the original draft of the manuscript; Bo Sun reviewed and edited the manuscript; Ming Wei administrated the project and performed funding acquisition. All authors have read and agreed to the published version of the manuscript.

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