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Article

Analysis of Pricing Decision of the High-Speed Railway under Airline's Competition: Based on the Same Route

Hao Li [1] and Ting Peng [1,*]

[1] School of Economics & Management, Chongqing Jiaotong University, 400074, China
* Correspondence: pt9509834@163.com

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Abstract: National policies on energy conservation and emission reduction call for the development of greener travel. The high-speed railway has irreplaceable advantages and status. At present, China's high-speed railway mainly adopts a fixed pricing strategy, which has demerits such as insufficient demand and reduced profits, so that high-speed railway has a distinct disadvantage when competing with aviation. Accordingly, we investigate the high-speed railway's optimal pricing strategy under the competition of airlines with the same route. Two pricing strategies are investigated for high-speed railway use: fixed pricing or dynamic pricing. Our analysis shows that dynamic pricing has positive effects on revenue and total social welfare. The development of high-speed railways is expected to play a major role in China's transition to a low-carbon and green economic growth model, which is emphasized by the results.

Keywords: Pricing, High-speed railway, Airline

1. Introduction

The greenhouse effect and global warming have attracted great attention at home and abroad in recent decades (Ipcc, 1995). In 2009, China promised that as a responsible country, it properly responds to climate change and implement a carbon emissions reduction plan. Further, in 2014, the Chinese government proposed to drop carbon dioxide emissions per unit of GDP dropped by 40–45% of 2005 levels by 2020(Zhou, Hu, and Zhou, 2018). As China has a great population (according to the 7th population census data in 2021, the Chinese mainland registered a population of 1.41 billion), the optimal choice of emission reduction technology is energy-saving, so the development of low-carbon travel becomes even more important. The research shows that the energy consumption of China's high-speed railway (HSR) is much lower than that of aviation under the same transportation condition, and the carbon dioxide emission is less than one-tenth of aviation's. Accordingly, it is significant to develop HSR as a low-carbon travel mode in China.

By the end of 2020, China's HSR had a total of 38,000 km, ranking first in the world. With the advantages of punctuality and convenience, HSR has a huge impact on civil aviation transportation along the same route. For example, after the operation of the Beijing-Taiyuan HSR, the airline's load factor dropped from 85 to 49%, and revenue decreased by 46%. In marketing, price serves as an effective tool for enterprises to increase market share and profits. Therefore, facing the competitive pressure brought by HSR, airlines have adopted a series of pricing policies to attract passengers, such as group purchase discounts and price reduction promotions. Instead, HSR's pricing is not flexible enough to accommodate demand sensitively (Zhang et al., 2018). Fixing pricing makes HSR have a weak position in market competition. Moreover, fixed pricing leads to a low attendance rate, which threatens to maximize the revenue of HSR. According to 2019 data, in China, there were only two profitable HSR lines (Beijing to Shanghai and Beijing to Guangzhou). Several segments had less than 50% occupancy. Given the present situation, it is necessary to reconsider the pricing strategy of HSR. Thus, on January 4, 2021, the work-group meeting of China National Railway Group Co., Ltd. was held in Beijing, in which it was mentioned to gradually promote the dynamic pricing mechanism of HSR.

However, scholars' opinions on dynamic pricing strategy are diverse (Xiong and Li, 2013; Yu et al., 2014). The supporters believe that dynamic pricing responds to market changes in time and increases revenue, while the opponents think that competition between HSR and airlines leads to a more fierce price war than before. Consequently, exploring the effectiveness of the pricing strategy of HSR is the key to solving the dilemma of HSR development. Thus, it is required for the following issues to be answered urgently. How does the dynamic pricing strategy affect the revenue of HSR? Will the change of pricing strategy of HSR help to improve total social welfare and form a low-carbon society? And what are the key points and difficulties in implementing the optimal pricing strategy? The in-depth research of these problems can provide an interpretation for China's transportation industry to formulate low-carbon sustainable development policies.

The remainder of the paper is structured as follows. After reviewing the related literature in section 2, we describe the model in section 3, and section 4 considers the equilibrium analysis under fixed pricing and dynamic pricing, respectively. In section 5, we report numerical exploration to obtain management insights. Finally, we provide conclusions and future research in section 6.

2. Literature Review

Pricing is a relatively mature analysis tool in revenue management theory, and its application in air transportation, hotel reservation, and other perishable goods industry fully demonstrates its practicability (Li, Xiong, and Xiong, 2013; He, Gan, and Yuan, 2019). Thus, we study the revenue management of HSR and airline from the perspective of perishable goods pricing. Chiang, Chen, and Xu (2007), Shen and Su (2010), Grauberger and Kimms (2016) studied the revenue management of airlines in a monopolized market. Researchers focused on techniques such as dynamic variation of price and seat inventory control of airlines (Ahn, Luo, and Shebalov, 2020; Garg, and Venkataraman, 2020). With further research, Zhang and Cooper (2009), Delahaye et al. (2017) discussed the pricing and revenue management of multiple products of airlines based on the competitive environment. In recent years, more research results have also been made on HSR, and its pricing strategy has always been the focus of theoretical circles (Liu et al., 2014).

There have been abundant research results on airlines or HSR, but most of them mainly showed the analysis of the revenue management and pricing of single transportation mode, while few studies focused on interactive competition between multiple products. Most studies fail to reflect the essence of the pricing problem of transportation enterprises in a better way. Therefore, from the perspective of the competition of multiple travel modes, scholars have analyzed the competition between HSR and airlines. Sato and Sawaki (2011) hypothesized that passengers could choose HSR, airline, or other transportations and analyzed the influence of factors (such as overselling and cancellation of passenger tickets) on the price. The study exhibited that the competition of air transportation reduced the price of HSR. Yang and Zhang (2012) analyzed the impact of airport travel time and HSR running speed on ticket prices and social welfare and concluded that cutting the price appropriately could lead to an increase in social welfare.

Intuitively, based on the competitive environment of HSR and airlines, the above research mainly analyzes the influence of various factors on ticket price and revenue. However, the substitution degree of HSR and air transport in China is changeable, and the pricing conflict is fierce. The pricing strategy of HSR has been explored by several researchers. For HSR to achieve a favorable position in the fierce market, Qin et al. (2019) proposed an innovative model to optimize the price and seat allocation for HSR simultaneously. The results showed that the model flexibly adjusts the price and seat allocation of the corresponding ticketing period according to the passenger demand and increases the total expected revenue by 5.92% without increasing the capacity. In response to the problems such as failure to improve revenue with current static and fixed prices of the same origin-destination (OD) in HSR, Zhu and Zha (2020) built the joint decision model of HSR dynamic pricing and ticket allocation. The findings indicate that the model improves the revenue and seat occupancy rate. Hence, it is useful and necessary to study the dynamic pricing strategy of HSR in the competitive environment.

Now, China has the largest HSR network in the world, but the revenue maximization of railway transportation corporations has not been realized, and China's HSR Corp is at a loss. In order to promote the sustainable development of HSR, the pricing model of HSR and airlines is constructed for independent decision-making on the same route. Further, it gives the equilibrium prices and revenue when dynamic pricing and fixed pricing are adopted by HSR. Subsequently, the effects of different market conditions on revenue are discussed. Additionally, we analyze the impact of two pricing strategies on total social welfare to provide decision support for the pricing of HSR.

3. Results

According to China Railway Corp, the national rail operator, sales of HSR tickets have been monopolized in China. Meanwhile, China Southern Airlines, Sichuan Airlines, and many other civil aviation passenger transport companies are selling airline tickets of the same origin and destination (Nie et al., 2019). Thus, HSR and airlines compete fiercely on the same routes, which influences the ticket price directly in their purchase decisions. Hence, the pricing of HSR and airline on the same route has been a critical issue in the field of traffic operation.

For tractability, the market is represented as an interactive competitive system of HSR (denoted by r), airline (denoted by a), and passengers. Supposing that the HSR and the airline compete on the same route, the entire sales are split into two periods (Period 1 and Period 2). Both companies offer tickets to the market at the beginning of the sales season, and the product has interchangeability. At the end of Period 2, tickets have a residual value of 0 (regardless of overselling and other circumstances). In the market, airlines usually adopt dynamic pricing, while HSR adopts fixed pricing (also exploring dynamic pricing under the guidance of national policy). Therefore, in the following, we analyze the fixed pricing and dynamic pricing for HSR separately.

(1) The airline adopts dynamic pricing and the HSR adopts fixed pricing, which is called (*F,D*) strategy and recorded as model *f*.

In Period 1, the HSR and the airline set the ticket price as $p_{1,r}^{f}$ and $p_{1,a}^{f}$. Since the HSR adopts fixed pricing, the ticket price of Period 2 is $p_{2,r}^{f}=p_{1,r}^{f}$. Based on the price of Period 1 and estimated demand, the airline decides that the price of Period 2 is $p_{2,a}^{f}$. Then passengers decide to buy now or wait according to $p_{1,r}^{f}$, $p_{1,a}^{f}$ and the expected price $p_{2,a}^{f}$. In Period 2, passengers decide to buy or leave the market based on $p_{2,a}^{f}$ and $p_{2,r}^{f}$.

(2) The airline adopts dynamic pricing, and the HSR adopts dynamic pricing, which is called (*D,D*) strategy and denoted as model *c*.

In Period 1, the HSR and the airline announced the ticket prices ($p_{1,r}^{c}$ and $p_{1,a}^{c}$). Meanwhile the HSR unveils the price discount factor δ of Period 2, similar to (Liu et al., 2012), where $0<\delta<1$ indicates that price reduction attracts passengers. Based on the sales volume of Period 1, the airline decides the ticket price of Period 2 ($p_{2,a}^{c}$). In Period 1, considering the ticket price and discount factor, passengers decide to buy immediately or wait. Further, passengers who wait until Period 2 decide to buy or leave the market based on the new price.

According to consumer utility theory, the passengers whose arbitrary perceptual valuation is θ would buy when arbitrary perceptual valuation $\theta' > \theta$. Suppose the indifference point of buying from HSR or airline is θ_2^j in Period 1, where $j=f,c$. The indifference point of buying ticket in Period 1 or buying it until Period 2 is θ_3^j, and the indifference point of buying from HSR or airline is θ_4^j in Period 2. Similar, the indifference point of buying from HSR or leaving the market is θ_5^j.

In this paper, the passenger's utility function is as follows.

$$U_i = \begin{cases} \theta - p_{t,a}, \textit{purchase from airline} \\ \beta\theta - p_{t,r}, \textit{purchase from high-speed railway} \end{cases} \tag{1}$$

Equation (1) represents the passenger's utility of purchasing from airline and HSR. It is worth noting that, β is substitutability of tickets between HSR and airline, which is understood as the level of differentiation between the products (Jiang and Zhang, 2016). Many factors, in reality, have an impact on β. Although within 500 km, passengers usually prefer HSR (i.e., $\beta>1$). However, without loss of generality, we mainly focus on the case of $0<\beta<1$. For example, when the distance is far, air travel has a time advantage (regardless of intra-city commuting costs and comfort), and the substitutability of HSR is weak. Therefore, when describing passenger utility, the substitutability between HSR and airline needs to be considered.

In addition, total social welfare is $U_z + \pi_a + \pi_r$. According to the utility function of the passenger, the total amount of passenger surplus is described

$$\begin{aligned} U_z = & \int_{\theta_5}^{\theta_4} \left(\beta\theta - p_{2,r}\right) f(\theta) d\theta + \int_{\theta_3}^{\theta_2} \left(\beta\theta - p_{1,r}\right) f(\theta) d\theta \\ & + \int_{\theta_4}^{\theta_3} \left(\theta - p_{2,a}\right) f(\theta) d\theta + \int_{\theta_2}^{1} \left(\theta - p_{1,a}\right) f(\theta) d\theta. \end{aligned} \tag{2}$$

When all passengers arrive at the market before the sale begins and each passenger can buy one ticket at most, the passengers' perceptions of the ticket are distributed uniformly on the interval [0,1]. Passengers are risk-neutral, so decide to buy tickets based on the comparison of two travel modes. The tickets are a typical perishable product, i.e., the value drops sharply over time. Therefore, it is assumed that the passengers' perceived discount is γ ($0<\gamma<1$) over Period 2, which indicates the degree of passenger's stratetegy. Higher γ means greater utility generated by the passenger's inter-temporal purchase (Dan, Zhang, and Zhou, 2018).

The specific parameter descriptions are shown in Table 1.

Table 1. Definition of variables.

Symbol	Variable Interpretation
β	Substitutability of tickets between railway and aviation, $0<\beta<1$
c	The cost of airline ticket, and the cost of railway ticket is βc (Prasad, Venkatesh, and Mahajan, 2015; Liu and Zhang, 2013), $0<c<1$
U_i	The utility of the passenger purchasing from HSR or airline
U_z	The sum of all the passengers' utilities in the market
π_i	The revenue of company i (i=a,r)
α	Discount factor of revenue in Period 2
$p_{t,i}$	The ticket price of company i (i=a,r) in Period t (t=1,2)
δ	Price discount factor of Period 2 (announced by the HSR)
γ	The passengers' perceived discount, $0<\gamma<1$

4. Analysis Equilibrium under Different Pricing Strategies

In this section, backward induction is introduced to analyze the optimal price and revenue of HSR and airline under (*F,D*) and (*D,D*) strategies, respectively.

4.1. Market Equilibrium Analysis under (*F,D*) *strategy*

This subsection discusses the market equilibrium in which the airline adopts dynamic pricing and the HSR adopts fixed pricing. Under (*F,D*) strategy , the total revenue of the HSR and the airline is expressed as

$$\begin{aligned}\pi_r^f &= \pi_{1,r}^f+\alpha\pi_{2,r}^f=\left(p_{1,r}^f-\beta c\right)\left(\theta_2^f-\theta_3^f\right)+\alpha\left(p_{2,r}^f-\beta c\right)\left(\theta_4^f-\theta_5^f\right),\\ \pi_a^f &= \pi_{1,a}^f+\alpha\pi_{2,a}^f=\left(p_{1,a}^f-c\right)\left(1-\theta_2^f\right)+\alpha\left(p_{2,a}^f-c\right)\left(\theta_3^f-\theta_4^f\right).\end{aligned} \tag{3}$$

4.1.1. Equilibrium Analysis of Period 2

According to the backward induction, we analyze Period 2 firstly. The HSR starts to compete with the airline in price. We have $\beta\theta_5^f-p_{2,r}^f=0$ and $\theta_4^f-p_{2,a}^f=\beta\theta_4^f-p_{2,r}^f$, which gives $\theta_5^f=\dfrac{p_{2,r}^f}{\beta}$ and $\theta_4^f=\dfrac{p_{2,a}^f-p_{2,r}^f}{1-\beta}$. In Period 2, there are three scenarios about the revenue of airlines and HSR.

(1) If all passengers purchase tickets from HSR, the passenger's utility should be satisfied $\beta\theta_4^f-p_{2,r}^f>\theta_4^f-p_{2,a}^f$. As a result, the revenue of airlines and HSR are calculated as

$$\begin{aligned}&\pi_{2,a}^f=0,\\ &\pi_{2,r}^f=\left(p_{2,r}^f-\beta c\right)\left(\theta_4^f-\frac{p_{2,r}^f}{\beta}\right).\end{aligned} \tag{4}$$

(2) When all passengers purchase tickets from airlines, we have $\beta\theta_5^f-p_{2,r}^f<0$, so the revenue of airline and HSR are

$$\begin{aligned}&\pi_{2,a}^f=\left(p_{2,a}^f-c\right)\left(\theta_3^f-p_{2,a}^f\right),\\ &\pi_{2,r}^f=0.\end{aligned} \tag{5}$$

(3) Passengers decide to purchase from HSR or airline. With $\beta\theta_4^f-p_{2,r}^f\le\theta_4^f-p_{2,a}^f$ and $\beta\theta_5^f-p_{2,r}^f\ge 0$, the revenue of airline and HSR in Period 2 are

$$\pi_{2,a}^f = \left(p_{2,a}^f - c\right)\left(\theta_3^f - \theta_4^f\right),$$
$$\pi_{2,r}^f = \left(p_{2,r}^f - \beta c\right)\left(\theta_4^f - \theta_5^f\right). \tag{6}$$

Accordingly, we obtain the following Theorem by backward induction.

Theorem 1. *Under the* (F,D) *strategy, the unique subgame Nash equilibrium in Period 2 is given by the price pair*

$$p_{2,a}^{f*} = \frac{c\beta}{2\gamma-\beta}, p_{1,r}^{f*} = p_{2,r}^{f*} = \frac{\gamma\beta c}{2\gamma-\beta}. \tag{7}$$

The corresponding revenue is

$$\pi_{2,a}^{f*} = \frac{4\left(c-\theta_3^f\right)^2(1-\beta)}{(4-\beta)^2}, \pi_{2,r}^{f*} = \frac{\beta\left(c-\theta_3^f\right)^2(1-\beta)}{(4-\beta)^2}. \tag{8}$$

4.1.2. Equilibrium Analysis of Period 1

In Period 1, the HSR competes for sales with the airline. Based on the passenger's choice, $\beta\theta_3^f - p_{1,r}^f = \gamma\theta_3^f - p_{2,a}^f$ and $\beta\theta_2^f - p_{1,r}^f = \theta_2^f - p_{1,a}^f$ are obtained, which gives $\theta_2^f = \frac{p_{1,a}^f - p_{1,r}^f}{1-\beta}$ and $\theta_3^f = \frac{p_{2,a}^f - p_{1,r}^f}{\gamma-\beta}$. Accordingly, the revenue function is defined as

$$\pi_a^f = \left(p_{1,a}^f - c\right)\left(1 - \frac{p_{1,a}^f - p_{1,r}^f}{1-\beta}\right) + \alpha(p_{2,a}^f - c)\left(\frac{p_{2,a}^f - p_{1,r}^f}{\gamma-\beta} - \frac{p_{2,a}^f - p_{2,r}^f}{1-\beta}\right),$$
$$\pi_r^f = \left(p_{1,r}^f - \beta c\right)\left(\frac{p_{1,a}^f - p_{1,r}^f}{1-\beta} - \frac{\gamma p_{2,a}^f - p_{1,r}^f}{\gamma-\beta}\right) + \alpha(p_{2,r}^f - \beta c)\left(\frac{p_{2,a}^f - p_{2,r}^f}{1-\beta} - \frac{p_{2,r}^f}{\beta}\right). \tag{9}$$

As HSR adopts fixed pricing, $p_{1,r}^{f*} = p_{2,r}^{f*}$. The second-order derivative of the airline's total revenue function is less than 0, so it is a concave function of price. Thus, $p_{1,a}^{f*} = \frac{(2\beta-3\gamma+1)\beta c}{(2\gamma+2)\beta-8\gamma+4} + \frac{c-\beta+1}{2}$ shows the unique equilibrium price of airlines. Substituting $p_{1,a}^{f*}$ into Eq. (9) and taking the derivative for price lead to the following.

The equilibrium prices and revenue of airlines and HSR in Period 2 are

$$p_{2,a}^{f*} = \frac{\left[3\beta-(\beta+2)\gamma+\right]c}{(\beta-4)\gamma+\beta+2}, p_{2,r}^{f*} = \frac{(2\beta-3\gamma+1)\beta c}{(\beta-4)\gamma+\beta+2},$$
$$\pi_{2,a}^{f*} = \frac{4(1-\beta)(\gamma-1)^2c^2}{\left[(\beta-4)\gamma+\beta+2\right]^2}, \pi_{2,r}^{f*} = \frac{\beta(1-\beta)(\gamma-1)^2c^2}{\left[(\beta-4)\gamma+\beta+2\right]^2}. \tag{10}$$

Therefore, the total two-period revenue of airline and HSR is

$$\pi_a^{f*} = \frac{(1-\beta)\left[\left(c-\frac{\gamma+1}{2}\right)\beta+(-2c+2)\gamma+c-1\right]^2 + 4(1-\beta)(\gamma-1)^2c^2\alpha}{\left[(\beta-4)\gamma+\beta+2\right]^2},$$
$$\pi_r^{f*} = \frac{\beta c(\gamma-1)(\beta-1)\left\{\left[-\frac{\beta}{2}+2+(-\alpha+2)c\right]\gamma+\left(c-\frac{1}{2}\right)\beta-1+(\alpha-3)c\right\}}{\left[(\beta-4)\gamma+\beta+2\right]^2}. \tag{11}$$

4.2. Market Equilibrium Analysis under (D,D) Strategy

Under (*D,D*) strategy, the total revenue of airline and HSR is calculated by

$$\pi_a^c = \pi_{1,a}^c + \alpha\pi_{2,a}^c = \left(p_{1,a}^c - c\right)\left(1-\theta_2^c\right) + \alpha\left(p_{2,a}^c - c\right)\left(\theta_3^c - \theta_4^c\right),$$
$$\pi_r^c = \pi_{1,r}^c + \alpha\pi_{2,r}^c = \left(p_{1,r}^c - \beta c\right)\left(\theta_2^c - \theta_3^c\right) + \alpha\left(p_{2,r}^c - \beta c\right)\left(\theta_4^c - \theta_5^c\right). \quad (12)$$

The inter-temporal pricing of airlines and HSR is also a two-period dynamic programming problem. Proceeding with the standard backward induction approach, the equilibrium prices and revenue can be further obtained.

4.2.1. Equilibrium Analysis of Period 2

At the beginning of Period 2, the HSR and airline announce the price simultaneously. Passengers compare the passenger's surplus to decide to choose HSR or airlines or withdraw from the market. The passenger's surplus of purchasing from airline or HSR is defined as $\theta_4^c - p_{2,a}^c$ and $\beta\theta_5^c - p_{2,r}^c$ respectively. Therefore, the valuation of the passenger who purchases from HSR in Period 2 needs to satisfy $\theta_4^c > \frac{p_{2,a}^c - p_{2,r}^c}{1-\beta}$. As there is no available air ticket, the airline's revenue is zero, and the HSR generates revenue of $\pi_{2,r}^c = \left(p_{2,L}^c - \beta c\right)\left(\theta_4^c - \frac{p_{2,r}^c}{\beta}\right)$. Similarly, when $\beta < \frac{p_{2,r}^c}{\theta_5^c}$, passengers purchase air tickets, the revenue of HSR is zero, and the airline's revenue is $\pi_{2,a}^c = \left(p_{2,a}^c - c\right)\left(\theta_3^c - p_{2,a}^c\right)$. If the HSR competes with the airline for sales in Period 2, namely $\beta\theta_4^c - p_{2,r}^c \le \theta_4^c - p_{2,a}^c$ and $\beta\theta_5^c - p_{2,r}^c \ge 0$. The revenue of airline and HSR are $\left(p_{2,a}^c - c\right)\left(\theta_3^c - \theta_4^c\right)$ and $\left(p_{2,r}^c - \beta c\right)\left(\theta_4^c - \theta_5^c\right)$.

From the above analysis, the following Theorem is obtained.

Theorem 2. *Under (D,D) strategy, the unique subgame Nash equilibrium in the last period is given by the price pair of*

$$p_{2,a}^{c*} = \frac{\beta c - 2\beta\theta_3^c + 2c + 2\theta_3^c}{4-\beta}, p_{2,r}^{c*} = \frac{\beta\left(3c + \theta_3^c - \beta\theta_3^c\right)}{4-\beta}. \quad (13)$$

The corresponding revenue is, then,

$$\pi_{2,a}^{c*} = \frac{4\left(c-\theta_3^c\right)^2\left(1-\beta\right)}{\left(4-\beta\right)^2}, \pi_{2,r}^{c*} = \frac{\beta\left(c-\theta_3^c\right)^2\left(1-\beta\right)}{\left(4-\beta\right)^2}. \quad (14)$$

4.2.2. Equilibrium Analysis of Period 1

At the beginning of Period 1, the HSR announces the price discount factor for Period 2. In Period 1, passengers decide to purchase from HSR or wait for an inter-period air ticket until Period 2. The indifference point θ_3^c satisfies the equation $\beta\theta_3^c - p_{1,r}^c = \gamma\theta_3^c - p_{2,a}^c$, namely, $\theta_3^c = \frac{p_{2,a}^c - p_{1,r}^c}{\gamma - \beta}$.

In Period 1, the passenger decides to purchase tickets from HSR or airlines. The indifference point θ_2^c is satisfied for $\beta\theta_2^c - p_{1,r}^c = \theta_2^c - p_{1,a}^c$, that is $\theta_2^c = \frac{p_{1,a}^c - p_{1,r}^c}{1-\beta}$. The equilibrium price of HSR in Period 1 is $p_{1,r}^{c*} = \frac{p_{2,r}^{c*}}{\delta} = \frac{\beta\left(3c + \theta_3^c - \beta\theta_3^c\right)}{\left(4-\beta\right)\delta}$. By substituting $p_{1,r}^{c*}$, $p_{2,a}^{c*}$ into θ_3^c, we have $\theta_3^{c*} = \frac{c\left(3\beta - \beta\delta - 2\delta\right)}{-B}$. Substituting θ_3^{c*} into $p_{1,r}^{c*}$ leads to

$p_{1,r}^{c*}=\frac{(3\gamma-2\beta-1)\beta c}{B}$. Since the airline adopts dynamic pricing, according to the revenue function, the equilibrium price is $p_{1,a}^{c*}=\frac{A}{2B}$, where

$$\begin{aligned}A&=(-\delta+1)\beta^3+\left[(c+\gamma+3)\delta-3c-2\right]\beta^2\\&\quad+\left[(-c-5)\gamma\delta-2c\delta+3c\gamma+1\right]\beta+4\delta(\gamma-\frac{1}{2})(c+1),\\B&=\left[\beta^2+(-\gamma-2)\beta+4\gamma-2\right]\delta-\beta^2+\beta.\end{aligned}$$

Accordingly, the revenue of airline and HSR is

$$\begin{aligned}\pi_{1,a}^{c*}&=\frac{(-2cB+A)\left[4\beta^2c+2B\beta+(-6\gamma+2)\beta c+A-2B\right]}{4B^2(\beta-1)},\\\pi_{1,r}^{c*}&=\frac{\beta(B+2\beta-3\gamma+1)\left[2c\beta^2(\delta-1)+2c\beta(\delta-3\gamma+4)-4c\delta+A\right]c}{2B^2(\beta-1)}.\end{aligned}\tag{15}$$

Therefore, the total revenue of two periods is calculated as

$$\begin{aligned}\pi_a^{c*}&=\frac{4c^2\alpha(1-\beta)\left[(\delta-3)\beta+2\delta-B\right]^2}{B^2(\beta-4)^2}\\&\quad+\frac{2\left(cB-\frac{A}{2}\right)\left[\frac{2(\beta-1)B+A}{4}+\frac{(\gamma+2\gamma\beta-3)\beta c}{2\gamma}\right]}{B^2(1-\beta)},\\\pi_r^{c*}&=\frac{\alpha c^2\beta(1-\beta)\left[(-\delta+3)\beta+B-2\delta\right]^2}{B^2(\beta-4)^2}\\&\quad+\frac{\beta(B+2\beta-3\gamma+1)\left[2c\beta^2(\delta-1)+2c\beta(\delta-3\gamma+4)-4c\delta+A\right]c}{2B^2(\beta-1)}.\end{aligned}\tag{16}$$

5. Analysis of Optimal Pricing Strategy for HSR

5.1. Price Analysis under (F,D) and (D,D) Strategies

By substituting the above values into Eq. (7), the price of HSR is lower than that of airlines under (*F,D*) strategy. Additionally, airlines are selling tickets at reduced prices in Period 2, which is consistent with the reality of clearance sales. Meanwhile, the following results are obtained, including the competitive relationship between the two transportation modes (HSR and airline).

(i) The price of HSR tickets rises based on the substitutability between HSR and airline, but it is still lower than that of airlines. Specifically, more passengers choose HSR (probably because of faster speed), and the increase in demand has driven the HSR's price to rise. However, because $0<\beta<1$, passengers' valuation of airlines is still higher.

(ii) The prices of HSR and airlines both decrease with the degree of passengers' strategy. When more passengers wait until the plane takes off or the high-speed train departures to purchase tickets, as mentioned earlier, both the airline and the HSR pursue maximum revenue, so they compete for passengers by cutting prices. That is, the higher degree of passengers' strategy intensifies the competition between HSR and airlines.

Under (D*,D*) strategy, we find the following.

(i) The price of the HSR in Period 1 decreases with the discount factor δ. As δ increases, (i.e., the discount rate of Period 2 is reduced), more passengers choose to buy in Period 1. Then, HSR has to lower prices to attract more passengers in Period 2, which forces airlines to reduce prices, too. Namely, the price change of airline tickets is synchronized with that of HSR.

(ii) With the increase of substitutability between HSR and airlines, in the same period, the price of HSR increases, and the price of airlines declines. The finding is also observed when the HSR adopts fixed pricing. In other words, the competitiveness of HSR has been improved and more passengers have been attracted, thus driving up its price, while airlines only cut the price to promote passengers to choose the plane.

5.2. Revenue Analysis under (F,D) and (D,D) Strategies

It is of interest to compare the revenue under *(F,D)* strategy with that of *(D,D)* strategy. In most cases, both the HSR and airlines gain more revenue from *(D,D)* strategy. That is, the implementation of dynamic pricing in HSR achieves Pareto improvements. The *(D,D)* strategy helps to alleviate fierce market competition and weaken the price conflict between railways and airlines. Through the adjustment of the HSR's pricing strategy, the two companies' revenues have increased simultaneously. It indicates that the strategy improves the development sustainability of the HSR. We also comment on how δ and β affect the revenue of two competitors, as described below.

(i) Under *(D,D)* strategy, the revenue of HSR and airlines decreases with the discount factor δ. The larger discount indicates that more passengers choose to purchase tickets in Period 1. The above findings are consistent with the price change trend, which also shows that "small profits but quick turnover" does not necessarily apply to passenger transport companies. In Period 2, the price of tickets is much lower than that of the previous period, resulting in the revenue loss of HSR and airlines in Period 2, and the total revenues of the two companies decline in the whole sales season.

(ii) As the substitutability between HSR and airline increases, the HSR's revenue increases while the airline's revenue decreases with different magnitude of the change. The higher the degree of substitutability about HSR, the more passengers choose to purchase HSR tickets, resulting in increasing the revenue. It is the same as the trend of price change. At the same time, the demand for air tickets is decreased by HSR, causing a loss of revenue. This happens in the real market. In China, after the opening of the Hefei Passenger Dedicated Line, the revenue of the Wuhan-Nanjing segment operated by Chengdu Airlines decreased by 41.5% in 2019.

5.3 Social Welfare Analysis under (F,D) and (D,D) Strategies

(i) In most cases, the total passenger surplus under (D*,D*) strategy is smaller than that of *(F,D)* strategy. It means that the strategy is beneficial for HSR to secure more passenger surplus, thereby increasing its revenue. Further comparison shows that the total passenger surplus increases with the discount factor, which means that the HSR ticket price concession of Period 2 is smaller, and the total utility of passengers is higher. This is because the increase of the discount factor conveys the information to the passengers that the price in Period 2 is higher. The passengers can purchase in Period 1 with greater utility, which in turn increases the valuation of the ticket, thus increasing the total passenger surplus.

(ii) When HSR adopts (*D,D*) strategy, the total surplus of passengers decreases with the degree of passenger's strategy. This shows that (*D,D*) strategy helps alleviate the strategic behavior of passengers. Regardless of the pricing strategy, the total passenger surplus increases with the degree of substitutability of HSR. This is because the advantage of the purchase of HSR ticket is increasingly prominent, and its price is lower than the air ticket. Passengers can buy tickets at low prices to meet their travel needs, so passengers have more leftovers.

To gain a deeper understanding of the effect of two strategies on total social welfare, we calculate the total social welfare as $U_z + \pi_a + \pi_r$.

(i) As the substitutability between HSR and airlines increases, total social welfare rises. When β increases (maybe the speed of HSR increases and the gap between HSR and airline decreases), passenger' utility improves. The increase of the HSR line and airlines' revenue has enhanced total social welfare. However, as the discount on HSR tickets decreases, the total social welfare declines. The reduction in the preferential rate of HSR tickets means that passengers need to pay higher prices to purchase tickets, which reduces the number of passengers. The reduction in the preferential margin also caused the HSR's revenue to decrease. The pressure of the decline in passenger utility and HSR's revenue forces the total social welfare to decline.

(ii) When the HSR adopts (*D,D*) strategy, the total social welfare is improved (but not necessarily for consumers). When the HSR adopts dynamic pricing, the price competition between HSR and airlines is alleviated, and the revenue increases. The adjustment of the pricing strategy of HSR promotes the increase of the total social welfare, which explains that the HSR's adoption of dynamic pricing contributes to the development of society and low-carbon economy.

6. Conclusions and Future Research

For the competition of HSR and airlines for the same route, we investigate whether dynamic pricing of HSR promotes the sustainable development of the market. Through the backward induction and equilibrium analysis, the following conclusion is drawn.

Compared with the two pricing strategies, dynamic pricing significantly increases the revenues of HSR and airlines. That is, Pareto improvement is realized. The increase of their revenue is regarded as "tacit collusion" between HSR and airlines. Moreover, when dynamic pricing is adopted by HSR, the total social welfare also improves with the increase of substitutability between HSR and airlines. This indicates that the adjustment of the pricing strategy promotes the development of the low-carbon industry in China so that the energy-saving mode of the HSR has greater development and sustainability, which helps to achieve an environment-friendly society.

To highlight China's contribution to emission-reduced travel, HSR ticket sales need to respond to policy guidance on time. When the low-carbon policy is implemented, the advantages of dynamic pricing encourage passengers to take HSR trains, which encourages the development of low-carbon travel mode with better revenue. Based on dynamic pricing, HSR determines the substitutability between HSR and airlines according to train's travel time and passing stations and carries out an appropriate pricing strategy with different times and lines to optimize the practicality of pricing strategy and improve the load rate of HSR trains.

Although the study result provides useful information, its limitations suggest interesting opportunities for future research. First, the analysis involves the competition between HSR and airlines for the same route. Thus, competition between HSR and airlines for multiple routes needs to be investigated more deeply in future research. Second, passengers have a different valuation for different mileage. For example, within 500 km, passengers usually prefer HSR. Many passengers choose their way of travel according to their comfort. Finally, the study on various pricing policies is suggested for future research.

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