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Modeling the effects of airline and high-speed rail cooperation on multi-airport systems: The implications on congestion, competition and social welfare

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Abstract

This paper investigates the effects of air and high-speed rail (HSR) cooperation on multi-airport systems (MAS). Two types of airport regimes are examined, namely profit-maximizing airports vis-à-vis welfare-maximizing airports. Stakeholders' decisions are analyzed in a vertical structure model and benchmarked across six scenarios characterizing the relationships between airports and between airline and HSR operator, under different airport ownership and objective regimes. Extensions to incorporating airline heterogeneity and air-HSR revenue sharing are also explored. The results suggest that in the case of profit-maximizing airports, (i) the effect of airport collaboration on the profit of transfer airport is ambiguous, regardless of air-HSR cooperation or not; (ii) although the air-HSR cooperation can enhance total profit of the airport system with airport collaboration, its effect is undetermined under airport non-collaboration; (iii) although the full cooperation can lead to the highest total profit of the airport system, it may not be the best scheme in terms of social welfare; (iv) In general, an airline is more likely to provide air-HSR inter-modal service in the presence of costly hub airport congestion, low degree of substitution between direct air service and air-HSR inter-modal service, or when the competition on the direct air route is not very significant. Air-HSR cooperation offers promising improvements to the MAS, and the associated welfare benefits would be more significant with inter-airport competition, especially in the case of profit-maximizing airports. Our study highlights the importance of maintaining inter-airport competition when air-HSR service is introduced into an MAS as an alternative to direct aviation services, and explains why subsidy to such service may be justified.

Keywords: Air-HSR cooperation; multi-airport system; airport ownership regime; profit-maximizing airport; welfare-maximizing airport.

1. Introduction

The past few decades have witnessed sustained and rapid growth of the aviation industry around the world. It was reported that in 2018, the annual throughput of each of the global top 22 busiest airports exceeds 60 million passengers. This nevertheless leads to severe congestion and delay. In 2019, nearly one in five flights in the United States was delayed by more than 15 minutes (BTS, 2020). Such a problem is particularly serious at hub airports (Fu et al., 2020), where traffic volume often exceeds designed capacity. For example, the designed capacity of Beijing Capital International Airport (PEK) was about 76 million passengers per year, which is much lower than its throughput of about 100 million passengers in 2018. The capacity insufficiency at hub airports also has negative impacts on airline competition. Dominant airlines can often charge a “hub premium” for their services, whereas capacity shortage and/or slot unavailability often restrict entrant airlines’ ability to compete effectively at hubs (Borenstein, 1989; Lijesen et al., 2001; the US Department of Transportation, 2001; Lee and Luengo-Prado, 2005; Fu et al., 2011; Sheng et al., 2019).

In many metropolitan regions, multi-airport system (MAS) is one promising, and sometimes “inevitable” solution (de Neufville, 1995), which can offer extra capacity and meanwhile introduce competition between airports. An MAS is a group of two or more adjacent airports that serve commercial traffic within a metropolitan region, enabling the air transportation system to adapt and evolve to meet travel demand (Bonnefoy, 2010). Indeed, MAS has been of growing importance in handling very large traffic volume (de Luca, 2012). However, there is no guarantee of the success of MAS, because the airport choices of passengers and airlines are usually affected by various factors (Pels et al., 2000, 2001, 2003). It is not uncommon that some airports in an MAS are under-utilized despite congestion at existing hubs (de Neufville and Odoni, 2003)[1], which leads to significant waste and inefficiency. de Neufville (1995) argued that an airport can only “*be a transport success if it is sufficiently attractive, in comparison with the alternative primary airport, to draw a sizable clientele…The attractiveness of an airport is always defined in comparison to its competition*”. However, secondary airports in many cases are not sufficiently competitive against the primary airport, as the latter has already developed convenient access and competitive aviation services.

[1] The under-utilization problem is not limited to secondary airports in a region. For example, the Washington Dulles airport and Newark Airport in New York had been under-utilized for many years although they had larger capacity than the existing hub airports (i.e. Reagan International and JFK airports, respectively).

Such a situation is changing with the introduction and growth of air-high speed rail (HSR) inter-modal services. In Europe, the AIRail service has been jointly offered by Deutsche Bahn (a Germany HSR company), Frankfort airport, and Lufthansa. In China, Spring Airlines promotes its air-HSR service to Beijing by flying passengers to the nearby Shijiazhuang Zhengding International airport (SJW), with a reimbursement of round-trip HSR tickets between Beijing and Shijiazhuang (Li and Sheng, 2016). Spring Airlines provides such an inter-modal service to Beijing because it could not procure the airport slots in Beijing (Fu et al., 2015; Wang et al., 2017). Table 1 lists the air-HSR passenger volume served by Spring Airlines at SJW during 2013-2018. It can be noted that the annual growth rate of the air-HSR passenger volume at SJW airport exceeds 40%, except for the year of 2015 when another airport close to Beijing, i.e., Tianjin Binhai International Airport (TSN), introduced a similar air-HSR integration service with an HSR ticket reimbursement scheme. Owing to a surging growth in the connecting passengers, such a reimbursement scheme at TSN airport was phased out in 2016 and thus the air-HSR passenger volume of SJW airport rebounded in that year.

Table 1 The air-HSR passenger volume of Spring Airlines at SJW airport in the past years.

Year	Passenger volume	Annual growth rate
2013	156,000	–
2014	225,000	44.23%
2015	253,000	12.40%
2016	412,000	62.85%
2017	737,000	78.69%
2018	1,132,000	53.60%

Such air-HSR service may impose significant impacts on MAS due to improved connectivity between airports. It could thus cause complex changes in related issues, such as the growth in passenger demand of secondary airports, competition between airlines, competition between airlines and air-HSR services, and changes in market equilibrium and social welfare. Such changes could lead to many unanswered questions, such as the policy decision of whether airports within an MAS should be encouraged to collaborate, or even managed under common control or ownership. For instance, consider the case that passengers flying from Shanghai to Beijing now have an option of flying to SJW first and then taking HSR to Beijing. Some passenger traffic can now be diverted from the hub airport (i.e., PEK) to the secondary airport (i.e., SJW). Intuitively, such a traffic adjustment could offer a potential opportunity of significant welfare gains, thanks to increased market competition with the introduction of air-HSR service and traffic shift from a congested hub to an under-utilized airport within the MAS. With increased HSR connectivity and air-HSR service, airports in an MAS may become more complementary. It is arguably more efficient for these airports to be managed by a single regulator so as to cooperate more closely. For example, all three major airports in the New York region (i.e. JFK, LaGuardia and Newark) are under the regulation of the Port Authority of New York and New Jersey. In 2014, the Chinese government launched a collaborative development program to promote airport collaboration in the metropolitan region around Beijing (i.e., Beijing-Tianjin-Hebei urban agglomeration region, or named as the "jing-jin-ji" region). This region, as shown in Fig. 1, is served by an MAS consisting of PEK airport (a hub airport), TSN airport, and SJW airport[2]. The designed capacities of the three airports are 76, 30, and 20 million passengers per year, respectively. However, the actual passenger throughput in 2018 were 100, 23.6, and 11.3 million passengers, implying that PEK airport is over-utilized, whereas TSN and SJW airports are both under-utilized. To achieve synergy through airport cooperation, the three airports have been jointly managed by the Capital Airport Holding Company (CAH) since 2015.

Fig. 1. Geographical locations of the Jing-jin-ji region in China.

However, such a centralized management of regional airports has aroused competition concerns and entirely opposite policies. For example, the UK Competition Commission forced the British Airport Authority (BAA) to sell the Gatwick Airport (Year of 2009) and the

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[2] In 2019, the Beijing Daxing International airport was put into operation, which is designed to be another major hub airport in the region.

Stansted Airport (Year of 2013) to promote airport competition in London.[3] This triggers a very interesting and important issue: which approach, airport collaboration or competition, makes better sense in terms of airport congestion reduction and social welfare improvement? Airport congestion and airport competition are among the two most critical issues for the airport industry, which seem to provide opposite recommendations on the relationship between airports within an MAS. Pagliari and Graham (2019) highlighted that "common or group ownership of airports poses a particular challenge for policy-makers". They carefully examined the performances of Edinburgh and Glasgow airports, which were under common ownership but separated in 2012. However, the investigation of such two nearby airports provided inconclusive findings on this important question. The introduction of air-HSR service may further complicate such a complex question. On the other hand, according to the previous related studies (e.g., Mun and Teraji, 2012; Noruzoliaee et al., 2015), the airport ownership regime (private or public) has an important impact on airport decisions (e.g., airport service qualities, airport regulatory schemes and airport charges), which influence the behavior of the airlines, HSR operator and the passengers. Indeed, the connectivity improvement due to introducing HSR between airports in an MAS and the availability of air-HSR service bring significant opportunities and challenges at the same time, triggering many new research issues and policy debates.

In light of the above discussion, this paper focuses on the investigations of the effects of the regional airport operating mechanisms and the air-HSR inter-modal services on the air and HSR systems. Six scenarios are formulated based on the relationship between airports in an MAS, the collaboration between airline and HSR operator in providing the air-HSR service, and the objectives of airports (i.e., profit-maximization or welfare-maximization, so that to proxy the airport ownership effects). Table 2 summarizes the six models, including four scenarios with profit-maximizing airports under the "private regime": (I) full non-cooperation (i.e., independent airline and HSR operator, with competitive airports in an MAS); (II) air-HSR non-cooperation but airport collaboration (i.e., independent airline and HSR operator, with collaborating airports in an MAS); (III) air-HSR cooperation and competing airports in an MAS (i.e., airline and the HSR operator jointly optimize the air-HSR service); (IV) full cooperation (i.e., airline and the HSR operator jointly optimize the air-HSR service, with

[3] The British Airport Authority was once the world's largest airport operator, managing seven British airports and twelve foreign airports. In 2009, the company was called to sell two airports in London, and one of Edinburgh or Glasgow airports in Scotland. In 2012, the company was renamed as Heathrow Airport Holdings in order to focus on operating Heathrow airport.

collaborating airports in an MAS). In addition, there are two scenarios in which airports maximize social welfare under the "public regime": (V) air-HSR non-cooperation (i.e., independent airline and HSR operator providing air-HSR service), and (VI) air-HSR cooperation (airline and HSR jointly optimize the air-HSR service). Market equilibria under these six scenarios are analyzed, together with a numerical study of the Shanghai-Beijing inter-city travel market. In addition, extensions incorporating direct HSR, airline heterogeneity, and air-HSR revenue sharing are also made so as to enhance the applicability of the proposed models to real cases.

Table 2 Six scenarios with different air-HSR services and regional airport operations.

	Private regime		**Public regime**
	Without airport collaboration	With airport collaboration	
Independent airline and HSR providing air-HSR service	I	II	V
Collaborating airline and HSR providing air-HSR service	III	IV	VI

This paper makes the following methodological and policy contributions. This study is among the first comprehensive analysis on the effects of air-HSR service on airports within an MAS. The effects of intra-MAS airport collaboration or competition, airline-HSR relationship, and airport ownership are analyzed simultaneously in an integrated model, which is solved and compared across different scenarios. This is a significant step forward compared to previous studies focused on particular issues over specific market structures. As shown in the subsequent analysis, these factors often have significant interrelations, ignoring which could lead to biased conclusions. More importantly, such a comprehensive model characterizes the key features of realistic markets, yielding some important insights and conclusions. Notably, the results suggest that the air-HSR cooperation helps airline and HSR to grow, and facilitates the traffic shift from a hub airport to nearby transfer airport. An airline is more likely to provide air-HSR inter-modal service in the presence of costly hub airport congestion, low degree of substitution between direct air service and air-HSR inter-modal service, or when the competition on the direct air route is not very significant. Air-HSR service has thus good potential to balance traffic volume within an MAS and to increase social welfare, which are otherwise difficult tasks at congested hub airports. Air-HSR cooperation offers promising improvements to the MAS, and the associated welfare benefits would be more significant with inter-airport competition, especially in the case of profit-maximizing airports. Our study highlights the importance of maintaining inter-airport competition when air-HSR service is introduced into an MAS as an alternative to direct aviation services.

The rest of the paper is organized as follows. Section 2 provides an overview of the relevant literature. Section 3 formulates the benchmark model in which the HSR service is not available. Section 4 solves and compares the model formulations across different scenarios. In Section 5, a numerical study of the Shanghai-Beijing inter-city travel market is conducted. Section 6 extends the proposed model to incorporate direct HSR, airline heterogeneity, and air-HSR revenue sharing. Section 7 provides conclusions and recommendations for further studies.

2. Literature review

In this section, we review the relevant literature, with a focus on the air-HSR competition and cooperation, and multi-airport systems, respectively.

2.1. Air-HSR competition and cooperation

Air-HSR competition and cooperation have recently become an important topic receiving significant attention, partly due to the rapid development of HSR in Asian and European markets. On the one hand, the HSR service is a competitive alternative to air transport, particularly on the short- and medium-haul routes (Vickerman, 1997; Park and Ha, 2006; Adler et al., 2010; Dobruszkes et al., 2014; Fu et al., 2014; Zhang et al., 2014; D'Alfonso et al., 2016; Jiang and Zhang, 2016; Xia and Zhang, 2016; Wang et al., 2017; Zhang et al., 2017; Wang et al., 2018; Su et al. 2020). HSR achieves competitive advantages in network connectivity, and journey time and cost in many markets (see, e.g., González-Savignat, 2004; Park and Ha, 2006; Roman et al., 2007; Fu et al., 2012; Yang and Zhang, 2012). In China, for instance, all the flights between Zhengzhou and Xi'an (with a haul distance of 503 km) were cancelled on March 25, 2010, only 48 days after the inauguration of the HSR service between these two cities. For the Wuhan-Guangzhou route with a distance of 1039 km, the number of the daily flights was reduced from 15 to 9 flights after introducing the HSR service in 2010. A literature review conducted by Zhang et al. (2019) showed that HSR can have a "traffic redistribution" effect, leading either to a more evenly distributed outcome, or to promote concentration to large airports.

On the other hand, there is a good potential for airline and HSR operators to cooperate or even integrate to provide the inter-modal services, which is another interesting issue. A few studies have focused on the transfer market, where HSR provides feeder services to aviation operations. Jiang et al. (2017) studied the performance of inter-modal services in the presence of domestic / international air-HSR partnerships. Xia et al. (2019) explored a revenue sharing mechanism between airline and HSR operators in a multi-airport region. Most of other studies considered simplified hub-and-spoke (HS) network structures with three nodes and two legs. For example, Socorro and Viecens (2013) analyzed the effects of air-HSR cooperation on social welfare and environment. Jiang and Zhang (2014) investigated how air-HSR cooperation influences the aviation market by considering hub airport capacity constraint and modal substitutability. After comparing the air-HSR competition and cooperation effects on the market, Xia and Zhang (2016) found that air-HSR cooperation is likely to be welfare-enhancing in a capacity-constrained airport. However, Xia and Zhang (2017) showed that unless the operating cost of the integrated mode is relatively low, the air-HSR cooperation is unlikely to be motivated. Li et al. (2018) investigated the factors influencing the air-HSR partnership level by empirically analyzing existing air-HSR cooperative arrangements around the world. Avenali et al. (2018) explored two strategic formations of air-HSR partnerships, namely a capacity purchase agreement and a joint venture agreement, and their effects on consumers and social welfare.

The aforementioned studies provide important insights and policy implications on the development of air-HSR service. However, few of them offered insights about the effect of the air-HSR service on multi-airport systems or regional airport systems. Air-HSR integration and cooperation may enhance the competitiveness of inter-modal services, attract more air-HSR passengers, and thus lead to more balanced passenger volume distribution between saturated and underutilized airports. Meanwhile, such developments would change the relationships between airports within an MAS. Therefore, it is important to systematically investigate the mechanisms and effects of airline-HSR cooperation on multi-airport systems, including synergy among airports, and effects on competition, congestion, market equilibrium and social welfare. As airport ownership forms play important roles in shaping the performance of airports and the downstream airline markets (Martin and Roman, 2001; Oum et al., 2003, 2006, 2008; Fu et al., 2011), it is also important to control for the effects of airport ownership regimes in multi-airport systems.

2.2. Multi-airport systems

The performance and mechanism of MAS have been studied in the literature, with explicit analysis on the interactions among passengers, airlines, and airports. For example, Hansen (1995) developed a positive feedback model that contributes to the understanding of the allocation of passenger traffic among the three main commercial airports of the San Francisco Bay Area, served by airports in Oakland, San Francisco, and San Jose. Using the nested logit model, Pels et al. (2000, 2001, 2003) investigated the origin airport choices of air passengers, together with airline choices or airport access mode choices in the San Francisco Bay Area. Loo (2008) empirically examined the significant factors contributing to passengers' airport choices in the MAS located at the Pearl River Delta, which consists of five international airports located in Hong Kong, Macau, Guangzhou, Shenzhen and Zhuhai. Pagliari and Graham (2019) stressed that airport ownership issue is an important challenge for policy-makers. Mun and Teraji (2012) studied flight allocation among airports in a metropolitan area through considering various airport ownership forms and regulatory schemes (centralized or decentralized). Noruzoliaee et al. (2015) discussed how privatization affects airports' capacity and pricing at two congested airports based on three scenarios with varying levels of privatization. These studies indicated that airport services (e.g., airport capacity, airport charge, flight allocation) in the regional airport system are heavily affected by airport ownership structures and regulatory schemes. Basso and Zhang (2007) investigated how facility competition affects facility capacities, charges and congestion delays with monopoly or duopoly facilities by a facility-carrier vertical structure. Zhang et al. (2010) and Saraswati and Hanaoka (2014) explored the airline-airport revenue sharing mechanisms with multiple airports and airlines, and the interactions among the mechanisms, airport / airline competition and social welfare. However, these previous relevant studies involving multi-airport systems seldom considered the effect of air-HSR inter-modal service, although the air-HSR mode would promote the redistribution of the aviation passenger volume and influence the interactions among the regional airports.

Some recent studies have discussed the role of HSR in redistributing traffic between airports and its effects on an MAS. For example, Takebayashi (2015) found that the improvement of connectivity between air and HSR at the airport can increase international passengers, and thus strengthens the airport's role as a gateway. Takebayashi (2016) showed that the collaboration between HSR and a low-demand airport can reduce congestion at a high-demand airport, and improve the social welfare of the system. Takebayashi and Onishi (2018) further considered an HSR line connecting a main and a reliever airport, and showed that providing fare support to HSR passengers can improve the robustness of aviation network through regaining passenger flow using the reliever airport. However, these studies usually treated HSR as a feeder service or did not explicitly consider the mechanism of air-HSR cooperation. Xia et al. (2019) analytically explored a revenue sharing mechanism between the airline and HSR operator providing air-HSR service within a multi-airport region. However, airports were not considered as decision makers, and thus the effects of important factors, such as the relationship between airports within an MAS (i.e., airport competition or cooperation), and airport ownership forms, were not systematically analyzed. In this paper, we consider four types of stakeholders, namely passengers, airlines, airports, and the HSR operator.[4] By considering these stakeholders' decisions in a vertical structure across different scenarios as summarized in Table 2, we can clearly identify and simultaneously control the effects of different factors, such as airport ownership, airport collaborative/competitive relationship, airline competition, and air-HSR and airline competition.

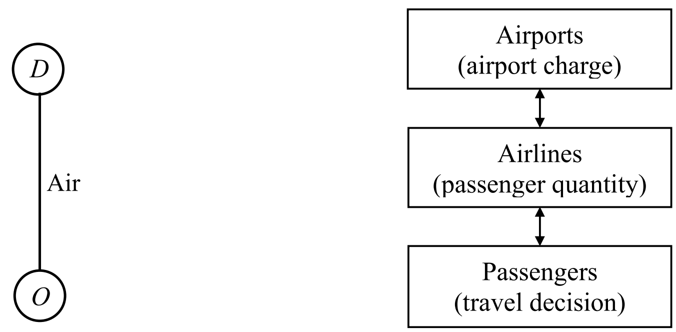
3. Model setup and the benchmark case without air-HSR service

In order to clearly identify the effects of the air-HSR service, in this section we examine the benchmark case, in which no air-HSR service is available.[5] That is, only direct flight services are available in the market. Consider an origin-destination (OD) pair, as shown in Fig. 2a, where the origin airport *O* is under-utilized while the destination airport *D* is a congested hub. Before introducing HSR service, the OD market is served by *N* competing airlines providing homogeneous services. The behaviors of the stakeholders (including passengers, airlines and airports) are modeled as a vertical structure, as shown in Fig. 2b: upstream airports serve airlines and determine their own service charges levied on airlines; airlines provide flight services to passengers and determine their passenger quantities (or equivalently flight frequencies with given aircraft size), whereas the downstream passengers decide to travel or not based on available services. Such a vertical-structured framework explicitly characterizes key stakeholders' decisions and has been widely adopted in the literature (e.g., Basso and

[4] In China, there is only one rail operator which provides all passenger and freight services. In 1987, the Japanese National Railways (JNR) was reformed into six regional passenger companies and one nationwide freight operator (Kurosaki, 2018). However, within each region there is only one HSR operator. In most other markets such as Korea, France and Germany, the dominant operator can be regarded as an effective monopoly.

[5] The HSR service in the world was first introduced in Japan in 1964 between Tokyo and Osaka, whereas the first European HSR service was introduced in 1977, linking Florence and Rome. In China, the first HSR service was introduced in 2008, linking Beijing and Tianjin.

Zhang, 2007; Barbot, 2009; Li et al., 2010; Zhang et al., 2010; Fu et al., 2011; Saraswati and Hanaoka, 2014; Xiao et al., 2016; Sheng et al., 2019).



(a) (b)

Fig. 2. Before introducing air-HSR service: (a) air market; (b) vertical market structure.

3.1. Travel cost and passenger demand

The travel cost (or full price) of passengers choosing airline *i*, denoted as ρ_i^a, consists of line-haul travel time cost, congestion delay cost at the destination hub airport, and airfare. ρ_i^a can be expressed as

$$\rho_i^a = \alpha t^a + \tau_i^a + D(F^a, K), \quad \forall i = 1, 2, \ldots, N, \tag{1}$$

where superscript "*a*" denotes the direct air transport mode. t^a is the line-haul travel time. α is the passengers' value of travel time, which is used to convert the travel time into the equivalent monetary cost. τ_i^a is the airfare of airline *i*. $D(F^a, K)$ is the congestion delay cost at the saturated hub airport, which is modeled as a function of the total number of flights F^a and the airport capacity *K*. It should be pointed out that in order to simplify the analysis, we assume in this paper that passengers know accurately the flight/train schedules prior to their departures, and waiting at airport or HSR stations are not explicitly modeled (i.e., equivalently wait time is zero).

Following the specification used in previous studies (e.g., Borger and Dender, 2006; Basso and Zhang, 2007; Yang and Zhang, 2011), the congestion delay can be calculated by

$$D(F^a, K) = \hat{\theta} \frac{F^a}{K}, \tag{2}$$

where F^a/K is the ratio of flight volume to capacity, and $\hat{\theta}$ denotes the passengers' marginal cost caused by airport congestion.

In this paper, all the competing airlines are assumed to be homogeneous, and they have the same type of aircraft and the same load factor. Such assumptions help derive analytical model solutions. Let *s* be the average number of passengers per flight. The total number of flights at the hub airport is thus obtained as

$$F^a = \frac{Q^a}{s}, \tag{3}$$

where $Q^a = \sum_{i=1}^{N} q_i^a$, Q^a is the total passenger volume or quantity by direct air service, and q_i^a is the passenger volume served by airline *i*.

The inverse passenger demand function is assumed to be linear (see e.g., Jiang and Zhang, 2014; D'Alfonso et al., 2016; Xiao et al., 2016), specified as

$$\rho_i^a = \beta_{OD} - b\sum_{i=1}^{N} q_i^a, \quad \forall i = 1,2,\ldots,N, \tag{4}$$

where intercept β_{OD} ($\beta_{OD} > 0$) can be interpreted as potential market size or service quality (Yang and Fu, 2015), and *b* ($0 < b \le 1$) is the slope of the demand function.

Let $\theta = \hat{\theta}/Ks$. The airfare τ_i^a of airline *i* can be obtained from Eqs. (1)-(4) as

$$\tau_i^a = \beta_{OD} - \alpha t^a - (b+\theta)\sum_{i=1}^{N} q_i^a, \quad \forall i = 1,2,\ldots,N. \tag{5}$$

3.2. Competitive airlines

Airlines are considered to be profit-driven, aiming to maximize their own profits by choosing passenger quantities. With given aircraft size and load factor, this is equivalent to an assumption of Cournot competition. The profit maximization problem for airlines can be formulated as

$$\max_{q_i^a} \ \pi_i^a(q_i^a) = (\tau_i^a - c^a - w^h)q_i^a, \quad \forall i = 1,2,\ldots,N, \tag{6}$$

where c^a is the marginal operating cost of airlines, and w^h is the service charge of the hub (destination) airport.

Setting $d\pi_i^a / dq_i^a = 0$ and applying the symmetry of homogeneous airlines, one can easily derive the Cournot-Nash equilibrium solution as

$$q_i^a = \frac{\beta^a - w^h}{(N+1)(b+\theta)}, \quad \forall i = 1, 2, \ldots, N, \tag{7}$$

where $\beta^a = \beta_{OD} - \alpha t^a - c^a$ denotes the welfare of a representative passenger using the direct air service.

Substituting Eq. (7) into $Q^a = \sum_{i=1}^{N} q_i^a$ and Eq. (5), one obtains the expressions for the total passenger volume by direct air service and the airfare of airline *i* as follows:

$$\begin{cases} Q^a = \dfrac{N(\beta^a - w^h)}{(N+1)(b+\theta)}, \\ \tau_i^a = c^a + w^h + \dfrac{\beta^a - w^h}{N+1}, \quad \forall i = 1, 2, \ldots, N. \end{cases} \tag{8}$$

Eq. (8) shows that airport congestion (reflected by the parameter θ) reduces airline traffic volume, whereas an airline's airfare is influenced by its operating cost, airport charge, and airline competition.

3.3. Airport decision

Two types of airports are considered in this study, namely profit-maximizing airports vs. welfare-maximizing airports. Such a modeling approach has been used for the analysis of ownership implications in the aviation industry. Privatized airports are generally regarded as more profit-driven, whereas public airports are believed to care more about social welfare (Czerny, 2013). Owing to regulation and practical constraints such as budget balance, in reality few airports can be characterized as pure profit or social welfare maximization. Profit-maximization and welfare-maximization nevertheless serve as useful benchmark cases for modeling the airport industry (Zhang and Zhang, 1997, 2003; Zhang and Czerny, 2012; Yang and Fu, 2015; Xiao et al., 2016, 2017). In particular, they can be used for the analysis of ownership effects, referred to as "private regime" and "public regime" for short in this paper.

3.3.1. Profit-maximizing airport

With marginal cost normalized to zero, an airport's profit is determined by the charge per passenger and passenger volume. The profit maximization problem for the hub destination airport (see Fig. 2a) can be formulated as

$$\max_{w^h} \Phi(w^h) = w^h \sum_{i=1}^{N} q_i^a \,, \tag{9}$$

where superscript "*h*" denotes the hub airport. q_i^a is the Cournot-Nash equilibrium solution of airline *i* given by Eq. (7).

From the first-order optimality condition of Eq. (9), one obtains the optimal airport charge as

$$w^{h(*)} = \frac{\beta^a}{2} \,, \tag{10}$$

where superscript " $*$ " denotes the optimal solution for the profit-maximization case. Substituting Eq. (10) into Eq. (7) yields the passenger quantity of airline *i* below

$$q_i^{a(*)} = \frac{\beta^a}{2(N+1)(b+\theta)}, \quad \forall i = 1, 2, \cdots, N \,. \tag{11}$$

Remark 1. Note that the optimal passenger quantity $q_i^{a(*)}$ is always positive. Accordingly, $\beta^a > 0$ and thus the optimal hub airport charge $w^{h(*)} > 0$ always holds.

By Eq. (9), the profit of the hub airport can be calculated as

$$\Phi^{h(*)} = \frac{N(\beta^a)^2}{4(N+1)(b+\theta)} \,. \tag{12}$$

In order to evaluate the effect of airport charge on the system, we examine the social welfare (SW), defined as the sum of consumer surplus, total profit of all airlines, and the airport's profit, as follows:

$$SW = \int_0^{Q^a} (\beta_{OD} - bx)\mathrm{d}x - \sum_{i=1}^{N} \rho_i^a q_i^a + \sum_{i=1}^{N} \pi_i^a + w^h Q^a \,, \tag{13}$$

where the difference between the first two terms on the right-hand side of Eq. (13) represents the consumer surplus, the third term is the total profit of all airlines, and the last term is the profit of the hub airport.

Substituting Eqs. (1), (6), (10) and (11) into Eq. (13) yields the social welfare below

$$SW^{(*)} = \frac{N\big((3N+4)b + 2(N+2)\theta\big)(\beta^a)^2}{8(N+1)^2(b+\theta)^2}. \tag{14}$$

According to Eqs. (12) and (14), the optimal profit of the hub airport and the social welfare are both increasing with the number of airlines *n*, showing the positive effects of airline competition.

3.3.2. Welfare-maximizing airport

A welfare-maximizing airport achieves its objective by choosing its charge, and thus its objective function can be expressed as

$$\max_{w^h} \; SW(w^h) = \int_0^{Q^a} (\beta_{OD} - bx)\mathrm{d}x - \sum_{i=1}^{N} \rho_i^a q_i^a + \sum_{i=1}^{N} \pi_i^a + w^h Q^a. \tag{15}$$

The corresponding first-order optimality condition leads to the optimal hub airport charge as

$$w^{h(**)} = \frac{\big((N-1)\theta - b\big)\beta^a}{N(b+2\theta)}, \tag{16}$$

where superscript "**" represents the optimal solution for the welfare-maximization case. The corresponding passenger quantity of airline *i*, the profit of the hub airport, and the total social welfare are, respectively, given as

$$\begin{cases} q_i^{a(**)} = \dfrac{\beta^a}{N(b+2\theta)}, \ \forall i = 1,2,\ldots,N, \\ \Phi^{h(**)} = \dfrac{\big((N-1)\theta - b\big)(\beta^a)^2}{N(b+2\theta)^2}, \\ SW^{(**)} = \dfrac{(\beta^a)^2}{2(b+2\theta)}. \end{cases} \tag{17}$$

Remark 2. The hub airport charge of the welfare-maximizing airport may be either positive or negative, depending on the sign of $(N-1)\theta - b$. When $(N-1)\theta - b < 0$ (i.e., $N < 1 + b/\theta$), in order to maximize social welfare, the hub airport subsidizes the airlines. The intuition is clear: when there is insufficient competition in the airline market, airline output (and thus traffic volume and flight frequency) would be sub-optimal. Subsidy is needed to induce higher traffic volume and flight frequency. When the number of competing airlines in the market is sufficiently large ($N \geq 1 + b/\theta$ in our model), airport charge is needed for the control of congestion. Correspondingly, the optimal profit of the hub airport may be positive or negative, depending on the sign of $(N-1)\theta - b$. The hub airport's profit increases with the number of competing airlines, or the total traffic volume. However, note that the social welfare does not change with the number of competing airlines, likely due to the moderating effects of airport charge, and the offsetting effects of airline competition on traffic volume and congestion. In summary, for a welfare-optimizing airport, airline competition does not improve social welfare, but can nevertheless increase the hub airport's profit or reduce subsidy to airlines.

Remark 3. Comparing the market outcomes of a profit-maximizing airport (private regime) and a welfare-maximizing airport (public regime), it can be concluded that

(i) The passenger quantity of profit-maximizing airport is lower than that of welfare-maximizing airport ($q_i^{a(*)} < q_i^{a(**)}$).

(ii) The optimal hub airport charge under the private regime is always higher than that under the public regime ($w^{h(*)} > w^{h(**)}$). The difference, i.e., $\Delta w^h = w^{h(*)} - w^{h(**)} = \dfrac{(N+2)b + 2\theta}{2N(b+2\theta)}$, decreases with the number of the competitive airlines, with a lower bound of $\dfrac{b}{2(b+2\theta)}$.

(iii) By definition, the profit of a profit-maximizing hub airport is higher than that of a welfare-maximizing airport ($\Phi^{h(*)} > \Phi^{h(**)}$). Reverse comparison result holds for the social welfare ($SW^{(*)} < SW^{(**)}$).

4. Model formulation with air-HSR service

With the availability of HSR service, the air-HSR mode becomes a transport alternative. Passengers have the option of using the air-HSR service by transferring at a connection airport (denoted as *T*), as depicted in Fig. 3a. That is, a passenger traveling from origin *O* to destination *D* can either choose a direct air service or the air-HSR inter-modal option. We consider that the airline on the air-HSR route is an entrant airline independent of carriers in the OD market, which is consistent with market reality observed in some of the routes (e.g., in China, Spring Airlines provides aviation services between airports in the cities of Shanghai and Shijiazhuang, many of its passengers then head to Beijing using HSR service). This implies that there are a total of *N* + 1 airlines in the market. There are four types of stakeholders, namely the passengers, airlines, the HSR operator and airports. Their behavior can also be characterized with a vertical structure as depicted in Fig. 3b: similar to the specification as in the benchmark case, upstream airports and downstream passengers make the same decisions related to airport charge and travel choice. The main difference is that now both airlines and the HSR operator provide transport services by choosing their respective passenger quantities. It should be pointed out that considering such a simplified network here aims to derive closed-form solutions to reveal the economic rationales and influencing factors for the modeling outcomes. In Section 6, we will further extend the model to include direct HSR, airline heterogeneity and air-HSR revenue-sharing mechanism. We will see that such extensions will lead to quite complicated solutions.

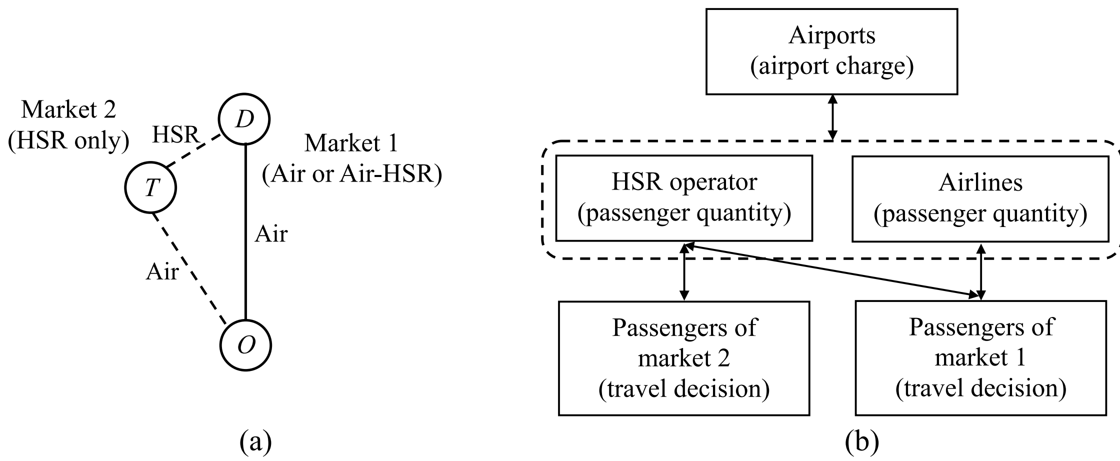


Fig. 3. After introducing air-HSR service: (a) two transport markets; (b) vertical structure of the markets.

In order to characterize the market reality in the aviation industry, in the following we discuss the public and private airport regimes in the context of an MAS. In the first type, the hub airport and the transfer airport are jointly managed to maximize social welfare. This resembles the case when airports are managed by a public group. For example, the Capital Airport Holding Company is a state corporation that manages 53 airports in China, including airports in the cities of Beijing and the nearby Tianjin and Shijiazhang. In the United States, the Port Authority of New York and New Jersey manages all three major airports in the region (i.e. JFK, LaGuardia and Newark). This regime is referred to as the “public regime” for easy reference.

In the second type (i.e., private regime), the hub airport and the transfer airport aim to maximize their individual profit. They may either collaborate or compete with each other. The collaborative case resembles the scenario in which private airports in a region are managed by the same company, such as the case in the Osaka metropolitan area of Japan. After the privatization in 2016, the Kansai Airport Group manages both the Kansai International Airport and the Osaka International Airport. In 2018, the company also took over the operations of the nearby Kobe Airport. The competition case resembles the scenario in which private airports in a region are separately managed, such as the major airports in London (i.e. Heathrow, Gatwick and Stansted). As summarized in Table 2, there are a total of four scenarios under the private regime and two scenarios under the public regime. In the following, all these scenarios are examined to identify the effects of air-HSR service in the context of an MAS.

4.1. Private regime with profit-maximizing airports

Under the private regime, four scenarios can be classified with respect to the air-HSR cooperation and/or airport collaboration as illustrated in Fig. 4. Scenario I represents the full non-cooperative case: the airline and HSR do not cooperate in providing the air-HSR inter-modal service, as depicted by the dotted lines linking the transfer airport. The hub and transfer airports do not collaborate and make independent decisions of airport charges, respectively. Scenarios II and III represent the cases of partial cooperation. Scenario II represents a case in which the airline and HSR do not cooperate in providing air-HSR service (depicted with dotted line), but both airports in the destination region collaborate, as depicted within the same block shape. Scenario III represents the case in which the entrant airline and HSR cooperate in providing the air-HSR service (with solid line), but the airports in the destination region do not collaborate (without block shape). Scenario IV represents the full cooperative case: the entrant airline and the HSR operator cooperate (with solid line), and both airports in the destination region collaborate with each other too (with block shape).

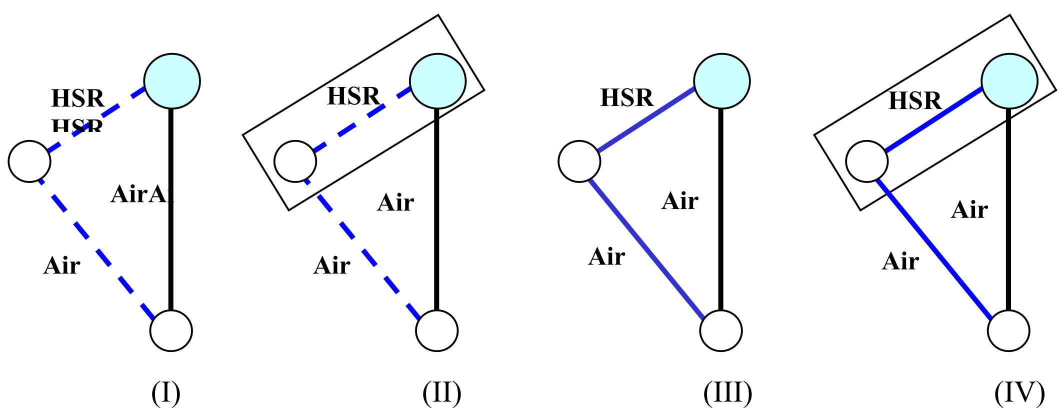


Fig. 4. The relationships between air and HSR and between hub and transfer airports.

4.1.1. Scenario I: full non-cooperation

For ease of presentation, we use superscript "*c*" to denote the combined air-HSR operation, and subscript "*k*" to denote the new entrant airline that provides air-HSR inter-modal service. As assumed, the transfer airport is underutilized and congestion-free. For Scenario I, the entrant airline and HSR make independent decisions related to air-HSR service, and thus the total ticket price for the combined air-HSR mode includes two separately chosen parts: airline *k*'s airfare and HSR ticket price. The total cost (or full price) of the air-HSR mode, represented as ρ_k^c, consists of costs related to the following components: en-route travel time t^c (which is the sum of air travel time and in-train travel time), connecting time Δt and transfer cost Δc incurred between the transfer airport and the HSR railway station, and the ticket price (which is the sum of airline *k*'s airfare τ_k^a and train fare τ^R). ρ_k^c can thus be expressed as

$$\rho_k^c = \alpha(t^c + \Delta t) + \Delta c + \tau_k^a + \tau^R. \tag{18}$$

The linear inverse demand functions for the direct air transport mode and the combined air-HSR mode are, respectively, defined as

$$\begin{cases} \rho_i^a = \beta_{OD} - b\sum_{i=1}^{N} q_i^a - \lambda q_k^c, \forall i = 1,2,\ldots,N, \\ \rho_k^c = \beta_{OD} - \lambda\sum_{i=1}^{N} q_i^a - bq_k^c, \end{cases} \tag{19}$$

where parameter λ ($0 \le \lambda \le b$) measures the substitutability or horizontal product differentiation between the direct air mode and the combined air-HSR mode, and q_k^c represents the number of passengers choosing the air-HSR service. With Eqs. (1), (18) and (19), the airfares of airlines on the direct air route and on the combined air-HSR route are expressed as

$$\begin{cases} \tau_i^a = \beta_{OD} - \alpha t^a - (b+\theta)\sum_{i=1}^{N} q_i^a - \lambda q_k^c, \ \forall i = 1,2,\ldots,N, \\ \tau_k^a = \beta_{OD} - \alpha(t^c + \Delta t) - \Delta c - \lambda\sum_{i=1}^{N} q_i^a - bq_k^c - \tau^R. \end{cases} \tag{20}$$

Note that in the market, there are a total of $N + 1$ airlines, i.e., N existing airlines and a new entrant airline k. Their profit maximization problems can be formulated as

$$\begin{cases} \max_{q_i^a} \pi_i^a(q_i^a) = (\tau_i^a - c^a - w^h)q_i^a, \ \forall i = 1,2,\ldots,N, \\ \max_{q_k^c} \pi_k^a(q_k^c) = (\tau_k^a - c^a - w^t)q_k^c, \end{cases} \tag{21}$$

where π_i^a is the profit of airline *i*, and π_k^a is the profit of airline *k*. w^t is the airport charge of the transfer airport, with superscript "*t*" representing transfer airport.

For the HSR market, we define its total cost ρ^R as the sum of the travel time cost and the HSR ticket price, i.e.,

$$\rho^R = \alpha t^R + \tau^R, \tag{22}$$

where superscript "*R*" denotes the pure HSR mode, t^R is the line-haul travel time of HSR service, and τ^R is the HSR ticket price.

The linear inverse demand function for the HSR mode is

$$\rho^R = \beta_{TD} - bq^R, \tag{23}$$

where β_{TD} is a parameter reflecting the market potential of the HSR market, and q^R is the number of HSR passengers. Note that the passengers on the HSR link consist of the passengers using the pure HSR mode (i.e., the passengers travelling between the transfer airport city and the hub airport city, i.e., "local passenger"), and the passengers using the air-HSR combined mode (i.e., "transfer passengers"). From Eqs. (22) and (23), the ticket price of HSR can be specified as

$$\tau^R = \beta_{TD} - \alpha t^R - bq^R. \tag{24}$$

The profit maximization problem of the HSR operator can thus be formulated as

$$\max_{q^R} \ \pi_{HSR}(q^R) = (\tau^R - c^R)q^R, \tag{25}$$

where c^R is the constant marginal operating cost of HSR.

From Eqs. (20), (21), (24), (25) and airlines symmetry, we can derive the passenger quantity solutions as follows:

$$
\begin{cases}
q_{i,I}^{a} = \dfrac{5b(\beta^{a} - w^{h}) - \lambda\left(2(\beta^{c} - w^{t} - c^{R}) - \beta^{R}\right)}{5bD - 2N\lambda^{2}}, \ \forall i = 1,2,\ldots,N, \\
q_{k,I}^{c} = \dfrac{-2N\lambda(\beta^{a} - w^{h}) + D\left(2(\beta^{c} - w^{t} - c^{R}) - \beta^{R}\right)}{5bD - 2N\lambda^{2}}, \\
q_{I}^{R} = \dfrac{\beta_{2}^{R}}{2b} + \dfrac{2N\lambda(\beta^{a} - w^{h}) - D\left(2(\beta^{c} - w^{t} - c^{R}) - \beta^{R}\right)}{2(5bD - 2N\lambda^{2})},
\end{cases}
\tag{26}
$$

where subscript "*I*" denotes Scenario I. $\beta^{c} = \beta_{OD} - a(t^{c} + \Delta t) - \Delta c - c^{a}$ and $\beta^{R} = \beta_{TD} - at^{R} - c^{R}$ denote the welfare of a representative passenger using air-HSR service and pure HSR service, respectively. For ease of presentation, we denote $D = (N+1)(b+\theta)$.

From Eqs. (20), (24), and (26), one can obtain the optimal airfare solutions for Scenario I as

$$
\begin{cases}
\tau_{i,I}^{a} = c^{a} + w^{h} + (b+\theta)q_{i,I}^{a}, \ \forall i = 1,2,\ldots,N, \\
\tau_{k,I}^{a} = c^{a} + w^{t} + bq_{k,I}^{c}, \\
\tau_{I}^{R} = c^{R} + \dfrac{-bN\lambda(\beta^{a} - w^{h}) + bD(\beta^{c} - w^{t} - c^{R}) + (2bD - N\lambda^{2})\beta^{R}}{5bD - 2N\lambda^{2}}.
\end{cases}
\tag{27}
$$

Eq. (27) shows that the airfare of each airline is determined by its marginal operating cost, airport charge and an extra cost related to the total passenger volume that it serves. The ticket price of the HSR service is determined by its marginal operating cost and an extra cost.

Comparing the passenger volume before and after introducing the air-HSR service, it is straightforward to obtain the following properties:

Proposition 1. Given airport charges, introducing air-HSR service leads to a decrease in the passenger volume on the direct air route, but an increase in the total passenger volume, i.e., $Nq_{i,I}^{a} < Nq_{i}^{a}$ and $Nq_{i,I}^{a} + q_{k,I}^{c} > Nq_{i}^{a}$.

Proposition 1 implies that introducing the HSR mode can attract more passengers into the transport market, although the passenger volume for each airline on the direct air route decreases. That is, the air-HSR service brings a "traffic stimulation" effect as well as a "traffic diversion" effect. The latter diverts some passengers from the direct air mode to the new inter-modal mode, and thus decreases the passenger volume at the hub airport. It should be noted that the "traffic stimulation" effect comes from two sources: with the introduction of one additional inter-modal service, passengers have more travel options and thus there is increased competition. A secondary effect is due to the congestion relief at the hub airport, which reduces passengers' full travel cost and thus attracts more passengers to travel. Note that the entrant airline provides the air-HSR service if and only if it is profitable to do so, i.e., $\pi_{k,I}^{a} > 0$, which yields

$$\frac{2(\beta^c - w^t - c^R)\text{-}\beta^R}{\beta^a - w^h} > \frac{\lambda}{b+\theta}\frac{2N}{N+1}. \quad (28)$$

This condition suggests that the new entrant airline has a strong motivation to serve the air-HSR market if the following conditions hold: (i) the air-HSR service offers higher value (i.e. a larger ratio of the willingness-to-pay of the transfer service and the pure HSR service to the willingness-to-pay of the direct air service), (ii) there are fewer competing airlines in the direct air market (i.e., N is smaller), (iii) the airport congestion delay is more costly (i.e., a larger θ), and (iv) when the direct air service and the air-HSR services are less substitutable (i.e., a smaller λ). The intuition is clear: when the air-HSR service offers more value and when there is less competition and substitution in the market, it will be easier and more profitable for the air-HSR to become a travel alternative to direct air service.

In Scenario I, the hub airport and the transfer airport do not collaborate, and each maximizes its own profit by choosing airport charge, formulated as

$$\begin{cases} \max\limits_{w^h} \ \Phi^h(w^h) = w^h \sum\limits_{i=1}^{N} q_{i,I}^{a}, \\ \max\limits_{w^t} \ \Phi^t(w^t) = w^t q_{k,I}^{c}, \end{cases} \quad (29)$$

where Φ^h and Φ^t, respectively, are the profits of the hub airport and the transfer airport.

From the first-order optimality condition of Eq. (29), the optimal airport charges of the hub and transfer airports can be obtained as

$$\begin{cases} w_I^{h(*)} = \dfrac{2(5bD - N\lambda^2)\beta^a - \lambda D\left(2(\beta^c - c^R) - \beta^R\right)}{2(10bD - N\lambda^2)}, \\ w_I^{t(*)} = \dfrac{-5bN\lambda\beta^a + (5bD - N\lambda^2)\left(2(\beta^c - c^R) - \beta^R\right)}{2(10bD - N\lambda^2)}. \end{cases} \quad (30)$$

Substituting Eq. (30) into Eq. (26), we can obtain the passenger quantity solutions as

$$\begin{cases} q_{i,I}^{a(*)} = \dfrac{10b(5bD-N\lambda^2)\beta^a - 5b\lambda D\left(2(\beta^c - c^R) - \beta^R\right)}{2(5bD-2N\lambda^2)(10bD-N\lambda^2)}, \ \forall i = 1,2,\ldots,N, \\ q_{k,I}^{c(*)} = \dfrac{-10bN\lambda D\beta^a + 2D(5bD-N\lambda^2)\left(2(\beta^c - c^R) - \beta^R\right)}{2(5bD-2N\lambda^2)(10bD-N\lambda^2)}, \\ q_I^{R(*)} = \dfrac{\beta^R}{2b} + \dfrac{5bN\lambda D\beta^a - D(5bD-N\lambda^2)\left(2(\beta^c - c^R) - \beta^R\right)}{2(5bD-2N\lambda^2)(10bD-N\lambda^2)}. \end{cases} \tag{31}$$

Remark 4. For the full non-cooperation scenario (i.e., Scenario I), both the optimal hub airport charge and the optimal transfer airport charge are positive, and the hub airport charge is higher than the transfer airport charge. When the HSR service becomes available, the hub airport charge will be reduced (i.e., lower than the charge in the benchmark case, or $w_I^{h(*)} < w^{h(*)}$). Therefore, although the air-HSR service alleviates the hub airport congestion, it reduces the profit of the hub airport.

Substituting the optimal airport charges in Eq. (30) into Eq. (28), one obtains the condition under which the entrant airline would like to provide the air-HSR service as

$$\frac{2(\beta^c - c^R) - \beta^R}{\beta^a} > \frac{5bN\lambda}{5b(b+\theta)(N+1) - N\lambda^2}. \tag{32}$$

4.1.2. Scenario II: air-HSR non-cooperation but airport collaboration

This scenario corresponds to the case when the hub and transfer airports collaborate with each other to maximize their total profit. Given the airport charges, the air passengers, the airlines and the HSR operator have the same decisions as in Scenario I, i.e., $q_{i,II}^a = q_{i,I}^a$, $\tau_{i,II}^a = \tau_{i,I}^a$ $(\forall i = 1,2,\ldots,N)$, $q_{k,II}^c = q_{k,I}^c$, $\tau_{k,II}^a = \tau_{k,I}^a$, $q_{II}^R = q_I^R$, and $\tau_{II}^R = \tau_I^R$, where subscript "*II*" denotes Scenario II. The airports' profit maximization problem is

$$\max_{w^h, w^t} \ \Phi(w^h, w^t) = w^h \sum_{i=1}^{N} q_{i,II}^a + w^t q_{k,II}^c, \tag{33}$$

where Φ is the total profit of the hub and transfer airports.

From the optimality condition of maximization problem (33), it can be derived that

$$\begin{cases} w_{II}^{h(*)} = \dfrac{\beta^a}{2}, \\ w_{II}^{t(*)} = \dfrac{\beta^c - c^R}{2} - \dfrac{\beta^R}{4}. \end{cases} \tag{34}$$

Eq. (34) shows that the hub airport charge and the transfer airport charge are both positive. Note that the line-haul travel time of air-HSR mode is longer than that of the direct air mode (i.e., $t^c > t^a$). Thus, $\beta^a - (\beta^c - c^R) = \alpha(t^c + \Delta t - t^a) + \Delta c + c^R$ is always positive and the hub airport charge is higher than the transfer airport charge.

Substituting Eq. (34) into the expressions of $q_{i,II}^a, q_{k,II}^c$ and q_{II}^R (see Eq. (26)) yields

$$\begin{cases} q_{i,II}^{a(*)} = \dfrac{5b\beta^a - \lambda\left(2(\beta^c - c^R) - \beta^R\right)}{2(5bD - 2N\lambda^2)}, \ \forall i = 1,2,\ldots,N, \\ q_{k,II}^{c(*)} = \dfrac{-2N\lambda\beta^a + D\left(2(\beta^c - c^R) - \beta^R\right)}{2(5bD - 2N\lambda^2)}, \\ q_{II}^{R(*)} = \dfrac{2N\lambda\beta^a - D\left(2(\beta^c - c^R) - \beta^R\right)}{4(5bD - 2N\lambda^2)} + \dfrac{\beta^R}{2b}. \end{cases} \tag{35}$$

Eqs. (34) and (35) show that in Scenario II, the optimal airport charges will not change with the number of competing airlines (i.e., N), while the corresponding passenger outputs will decrease with the number of competing airlines, regardless of on the direct route or on the air-HSR route. Therefore, we can conclude that the fierce airline competition on the direct route will reduce the total airport profit. The condition for the new airline entry ($\pi_{k,II}^{a(*)} > 0$) can be obtained as

$$\frac{2(\beta^c - c^R) - \beta^R}{\beta^a} > \frac{2N\lambda}{(b+\theta)(N+1)}. \tag{36}$$

Comparing Scenarios I and II, we have the following properties:

Proposition 2. When the entrant airline and the HSR operator do not cooperate and make independent decisions in providing the air-HSR services,

(i) Regional airport collaboration raises charges at both the hub airport and the transfer airport, i.e., $w_I^{h(*)} < w_{II}^{h(*)}$ and $w_I^{t(*)} < w_{II}^{t(*)}$.

(ii) Regional airport collaboration reduces the passenger output on the direct air route ($q_{i,I}^{a(*)} > q_{i,II}^{a(*)}$), the passenger output on the air-HSR route ($q_{k,I}^{c(*)} > q_{k,II}^{c(*)}$), and the HSR passenger volume ($q_{k,I}^{c(*)} + q_{I}^{R(*)} > q_{k,II}^{c(*)} + q_{II}^{R(*)}$). However, the regional airport collaboration will increase the passenger volume for the pure HSR market ($q_{I}^{R(*)} < q_{II}^{R(*)}$).

4.1.3. Scenario III: air-HSR cooperation but airport non-collaboration

In Scenario III, entrant airline and the HSR cooperate to jointly provide the air-HSR service as a single decision maker. The total travel cost of the air-HSR service is given as

$$\rho_k^c = \alpha(t^c + \Delta t) + \Delta c + \tau_k^c, \tag{37}$$

where τ_k^c is the integrated ticket price of the air-HSR service. In Scenario I, airline and HSR do not cooperate, thus the airfare and the HSR ticket price are separately chosen by the two operators. In comparison, in Scenario III, one single air-HSR price is jointly chosen by the air and HSR operators.

From Eqs. (1), (19), (22), (23) and (37), we can obtain

$$\begin{cases} \tau_i^a = \beta_{OD} - \alpha t^a - (b+\theta)\sum_{i=1}^{N} q_i^a - \lambda q_k^c, \ \forall i = 1,2,...,N, \\ \tau_k^c = \beta_{OD} - \alpha(t^c + \Delta t) - \Delta c - \lambda \sum_{i=1}^{N} q_i^a - b q_k^c, \\ \tau^R = \beta_{TD} - a t^R - b q^R. \end{cases} \tag{38}$$

With the cooperation between the entrant airline and the HSR operator, they can be seen as one single operator jointly determining the passenger output of the air-HSR mode q_k^c and the passenger output of the pure HSR mode q^R. The objective functions of the $N + 1$ operators (i.e., one air-HSR service operator and *n* airlines) in the system are

$$\begin{cases} \max_{q_i^a} \ \pi_i^a(q_i^a) = (\tau_i^a - c^a - w^h) q_i^a, \ \forall i = 1,2,\ldots,N, \\ \max_{q_k^c, q^R} \ \pi^c(q_k^c, q^R) = (\tau_k^c - c^a - c^R - w^t) q_k^c + (\tau^R - c^R) q^R - C_F, \end{cases} \tag{39}$$

where π^c is the total profit of the air-HSR service operator, and $C_F > 0$ represents the sunk cost caused by the cooperation of airline *k* and the HSR company.

Based on Eqs. (38) and (39), we can derive the passenger output and fare solutions as follows.

$$
\begin{cases}
q_{i,III}^{a} = \dfrac{2b(\beta^{a} - w^{h}) - \lambda(\beta^{c} - w^{t} - c^{R})}{2bD - N\lambda^{2}}, \ \forall i = 1,2,\ldots,N, \\
q_{k,III}^{c} = \dfrac{-N\lambda(\beta^{a} - w^{h}) + D(\beta^{c} - w^{t} - c^{R})}{2bD - N\lambda^{2}}, \\
q_{III}^{R} = \dfrac{\beta^{R}}{2b}, \\
\tau_{i,III}^{a} = c^{a} + w^{h} + (b+\theta)q_{i,III}^{a}, \\
\tau_{k,III}^{c} = c^{a} + c^{R} + w^{t} + bq_{k,III}^{c}, \\
\tau_{III}^{R} = c^{R} + bq_{III}^{R},
\end{cases}
\tag{40}
$$

where subscript "*III*" represents Scenario III. Again, the ticket price of the direct air mode includes the marginal operating cost of the airline, the airport charge and an extra charge related to the total number of passengers served by the specific airline. However, the ticket price of the air-HSR integration mode has an additional cost, namely the marginal operating cost of HSR c^R, because the airline and the HSR in the air-HSR integration mode are treated as one operator.

Given the airport charges, the differences of ticket prices paid by the passengers on the direct air route and on the air-HSR integration route in Scenarios I and III are, respectively, given as

$$
\begin{cases}
\tau_{i,III}^{a} - \tau_{i,I}^{a} = \lambda(b+\theta)\dfrac{bN\lambda(\beta^{c} - w^{h}) - bD(\beta^{c} - w^{t} - c^{R}) - \left(2bD - N\lambda^{2}\right)\beta^{R}}{\left(2bD - N\lambda^{2}\right)\left(5bD - 2N\lambda^{2}\right)} < 0, \\
\tau_{k,III}^{c} - (\tau_{k,I}^{c} + \tau_{I}^{R}) = \left(bD - N\lambda^{2}\right)\dfrac{bN\lambda(\beta^{a} - w^{h}) - bD(\beta^{c} - w^{t} - c^{R}) - \left(2bD - N\lambda^{2}\right)\beta^{R}}{\left(2bD - N\lambda^{2}\right)\left(5bD - 2N\lambda^{2}\right)} < 0.
\end{cases}
\tag{41}
$$

According to Eq. (41), we have the following properties:

Proposition 3. Given the airport charges for the non-collaborated airports,
(i) The airfare of the direct air mode with entrant airline-HSR cooperation is lower than that when the two operators make independent decisions.
(ii) The integrated ticket price with entrant airline-HSR cooperation is lower than the sum of the airfare and train fare when the two operators make independent decisions.

Proposition 3 shows that the cooperation between the entrant airline and the HSR lowers the fares on both direct air and air-HSR routes, and thus benefits all passengers in the air market.

We now look at the airports' behavior. The profit-maximization objectives of the hub and transfer airports are

$$\begin{cases} \max_{w^h} \ \Phi^h(w^h) = w^h \sum_{i=1}^{N} q_{i,III}^a, \\ \max_{w^t} \ \Phi^t(w^t) = w^t q_{k,III}^c. \end{cases} \tag{42}$$

The optimal solutions for the charges of the two airports can be derived as

$$\begin{cases} w_{III}^{h(*)} = \dfrac{(4bD - N\lambda^2)\beta^a - \lambda D(\beta^c - c^R)}{8bD - N\lambda^2}, \\ w_{III}^{t(*)} = \dfrac{-2N\lambda b\beta^a + (4bD - N\lambda^2)(\beta^c - c^R)}{8bD - N\lambda^2}. \end{cases} \tag{43}$$

The corresponding optimal passenger output solutions are

$$\begin{cases} q_{i,III}^{a(*)} = 2b\dfrac{(4bD - N\lambda^2)\beta^a - \lambda D(\beta^c - c^R)}{(2bD - N\lambda^2)(8bD - N\lambda^2)}, \ \forall i = 1,2,\ldots,N, \\ q_{k,III}^{c(*)} = D\dfrac{-2N\lambda b\beta^a + (4bD - N\lambda^2)(\beta^c - c^R)}{(2bD - N\lambda^2)(8bD - N\lambda^2)}, \\ q_{III}^{R(*)} = \dfrac{\beta^R}{2b}. \end{cases} \tag{44}$$

According to the optimal passenger outputs in Eq. (44), at equilibrium both the hub airport charge and the transfer airport charge (i.e., Eq. (43)) are positive. However, the relative size of the two airport charges is ambiguous. As $\frac{\beta^c - c^R}{\beta^a} < \frac{4bD - N\lambda^2 + \lambda D}{4bD - N\lambda^2 + 2N\lambda b}$, the hub airport charge is higher than the transfer airport charge. Otherwise, the hub airport charge may be lower.

Proposition 4. When the hub airport and transfer airport make separate decisions,

(i) The entrant airline-HSR cooperation reduces the airport charge of the hub airport ($w_{III}^{h(*)} < w_I^{h(*)}$), but increases the airport charge of the transfer airport ($w_{III}^{t(*)} > w_I^{t(*)}$).

(ii) The entrant airline-HSR cooperation reduces the passenger output on the direct air route ($q_{i,III}^{a(*)} < q_{i,I}^{a(*)}$), while increases the passenger output both on the air-HSR route ($q_{k,III}^{c(*)} > q_{k,I}^{c(*)}$) and on the pure HSR route ($q_{III}^{R(*)} > q_I^{R(*)}$).

According to Proposition 4, the entrant airline-HSR cooperation reduces the profit of the hub airport, while increases the transfer airport's profit. The condition for entrant airline's positive profit (i.e., $(\tau_{k,III}^{c(*)} - c^a - c^R - w_{III}^{t(*)})q_{k,III}^{c(*)} > 0$) can be rewritten as

$$\frac{\beta^c - c^R}{\beta^a} > \frac{2bN\lambda}{4b(b+\theta)(N+1) - N\lambda^2}. \tag{45}$$

4.1.4. Scenario IV: full cooperation

In the full cooperation case, the entrant airline and the HSR operator on the air-HSR route cooperate, and thus the behavioral decisions of airlines and the HSR operator are the same as those in Scenario III, i.e., $q^a_{i,IV} = q^a_{i,III}$, $\tau^a_{i,IV} = \tau^a_{i,III}$ $(\forall i = 1, 2, \ldots, N)$, $q^c_{k,IV} = q^c_{k,III}$, $\tau^c_{k,IV} = \tau^c_{k,III}$, $q^R_{IV} = q^R_{III}$, and $\tau^R_{IV} = \tau^R_{III}$. On the other hand, the hub airport and transfer airport cooperation means that they maximize the joint airport profit, specified as

$$\max_{w^h, w^t} \ \Phi(w^h, w^t) = w^h \sum_{i=1}^{N} q^a_{i,IV} + w^t q^c_{k,IV}, \tag{46}$$

where subscript "*IV*" represents Scenario IV. Solving the maximization problem (46) yields the optimal airport charges below

$$\begin{cases} w^{h(*)}_{IV} = \dfrac{\beta^a}{2}, \\ w^{t(*)}_{IV} = \dfrac{\beta^c - c^R}{2}. \end{cases} \tag{47}$$

Remark 6. With the full cooperation, the airport charges at both airports are positive. The hub airport charge is higher than the transfer airport charge because $\beta^a > \beta^c - c^R$ always holds.

The corresponding passenger quantities can be solved as

$$\begin{cases} q^{a(*)}_{i,IV} = \dfrac{2b\beta^a - \lambda(\beta^c - c^R)}{2(2bD - N\lambda^2)}, \ \forall i = 1, 2, \ldots, N, \\ q^{c(*)}_{k,IV} = \dfrac{-N\lambda\beta^a + (b+\theta)(N+1)(\beta^c - c^R)}{2(2bD - N\lambda^2)}, \\ q^{R(*)}_{IV} = \dfrac{\beta^R}{2b}. \end{cases} \tag{48}$$

In Scenario IV, the condition for the entrant airline's positive profit $(\tau^{c(*)}_{k,IV} - c^a - c^R - w^{t(*)}_{IV}) q^{c(*)}_{k,IV} > 0$ can be rewritten as

$$\frac{\beta^c - c^R}{\beta^a} > \frac{N\lambda}{(b+\theta)(N+1)}. \tag{49}$$

Comparing Scenarios III and IV, we have the following properties:

Proposition 5. If entrant airline and HSR cooperate to provide the integrated air-HSR service,
(i) The airport collaboration raises both the hub airport charge and the transfer airport charge ($w_{IV}^{h(*)} > w_{III}^{h(*)}$, and $w_{IV}^{t(*)} > w_{III}^{t(*)}$).
(ii) The airport collaboration reduces the passenger output on the direct air route ($q_{i,IV}^{a(*)} < q_{i,III}^{a(*)}$), the passenger output on the air-HSR route ($q_{k,IV}^{c(*)} < q_{k,III}^{c(*)}$) and the passenger output on the HSR route ($q_{k,IV}^{c(*)} + q_{IV}^{R(*)} < q_{k,III}^{c(*)} + q_{III}^{R(*)}$). But, it would not change the passenger volume of the pure HSR mode ($q_{IV}^{R(*)} = q_{III}^{R(*)}$).

According to Proposition 5, with the entrant airline-HSR cooperation, the airport collaboration reduces the passenger volumes at the hub and transfer airports, while increases their total profit. However, airport collaboration or non-collaboration has no effect on the passenger volume on the pure HSR service linking the hub and transfer airport cities.

We further compare the market equilibria between the scenarios, notably on airport charges, airport profits, and passenger outputs, as summarized in Tables 3 and 4. Table 3 focuses on the effects of airport collaboration, whereas Table 4 focuses on the effects of the air-HSR cooperation.

Table 3 The effects of the airport collaboration under the private regime.

Solution	**Scenario I vs II**	**Scenario III vs IV**
Airport charge of hub airport	$w_I^{h(*)} < w_{II}^{h(*)}$	$w_{III}^{h(*)} < w_{IV}^{h(*)}$
Airport charge of transfer airport	$w_I^{t(*)} < w_{II}^{t(*)}$	$w_{III}^{t(*)} < w_{IV}^{t(*)}$
Passenger output on direct air route	$q_{i,I}^{a(*)} > q_{i,II}^{a(*)}$	$q_{i,III}^{a(*)} > q_{i,IV}^{a(*)}$
Passenger output on air-HSR route	$q_{k,I}^{c(*)} > q_{k,II}^{c(*)}$	$q_{k,III}^{c(*)} > q_{k,IV}^{c(*)}$
Passenger output on HSR route	$q_{k,I}^{c(*)} + q_I^{R(*)} > q_{k,II}^{c(*)} + q_{II}^{R(*)}$	$q_{k,III}^{c(*)} + q_{III}^{R(*)} > q_{k,IV}^{c(*)} + q_{IV}^{R(*)}$
Passenger output on pure HSR market	$q_I^{R(*)} < q_{II}^{R(*)}$	$q_{III}^{R(*)} = q_{IV}^{R(*)}$
Profit of hub airport	$\Phi_I^{h(*)}$ £ $\Phi_{II}^{h(*)}$	$\Phi_{III}^{h(*)} < \Phi_{IV}^{h(*)}$
Profit of transfer airport	$\Phi_I^{t(*)}$ £ $\Phi_{II}^{t(*)}$	$\Phi_{III}^{t(*)}$ £ $\Phi_{IV}^{t(*)}$
Total profit of airports	$\Phi_I^{(*)} < \Phi_{II}^{(*)}$	$\Phi_{III}^{(*)} < \Phi_{IV}^{(*)}$

Table 4 The effects of the air-HSR cooperation under the private regime.

Solution	Scenario I vs III	Scenario II vs IV
Airport charge of hub airport	$w_I^{h(*)} > w_{III}^{h(*)}$	$w_{II}^{h(*)} = w_{IV}^{h(*)}$
Airport charge of transfer airport	$w_I^{t(*)} < w_{III}^{t(*)}$	$w_{II}^{t(*)} < w_{IV}^{t(*)}$
Passenger output on direct air route	$q_{i,I}^{a(*)} > q_{i,III}^{a(*)}$	$q_{i,II}^{a(*)} > q_{i,IV}^{a(*)}$
Passenger output on air-HSR route	$q_{k,I}^{c(*)} < q_{k,III}^{c(*)}$	$q_{k,II}^{c(*)} < q_{k,IV}^{c(*)}$
Passenger output on HSR route	$q_{k,I}^{c(*)} + q_I^{R(*)} < q_{k,III}^{c(*)} + q_{III}^{R(*)}$	$q_{k,II}^{c(*)} + q_{II}^{R(*)} < q_{k,IV}^{c(*)} + q_{IV}^{R(*)}$
Passenger output on pure HSR market	$q_I^{R(*)} < q_{III}^{R(*)}$	$q_{II}^{R(*)} < q_{IV}^{R(*)}$
Profit of hub airport	$\Phi_I^{h(*)} > \Phi_{III}^{h(*)}$	$\Phi_{II}^{h(*)} > \Phi_{IV}^{h(*)}$
Profit of transfer airport	$\Phi_I^{t(*)} < \Phi_{III}^{t(*)}$	$\Phi_{II}^{t(*)} < \Phi_{IV}^{t(*)}$
Total profit of airports	$\Phi_I^{(*)}$ £ $\Phi_{III}^{(*)}$	$\Phi_{II}^{(*)} < \Phi_{IV}^{(*)}$

Tables 3 and 4 lead to Summary 1 as follows:

Summary 1. For profit-maximizing airports, the following conclusions with respect to airport charge, passenger output and airport profit can be obtained

(i) ***Airport charge***: collaboration between the hub and transfer airports enhances the airport charges, regardless of air-HSR cooperation or not. The air-HSR cooperation lowers the hub airport charge absent airport collaboration, otherwise has no effect on the hub airport charge when the hub and transfer airports are collaborative. For the transfer airport, the air-HSR cooperation always leads to an increase in its airport charge, regardless of airport collaboration or not.

(ii) ***Passenger output***: airport collaboration can reduce the airlines' passenger quantities and the total passenger volume on the HSR route, regardless of air-HSR cooperation or not. However, the airport collaboration will not decrease the OD passenger volume between transfer airport city and hub airport city. Air-HSR cooperation always reduces the passenger output on the direct air route and increases the passenger outputs on other routes. Both air-HSR cooperation and airport collaboration can alleviate the hub airport congestion, with the full cooperation bringing the most significant effects.

(iii) ***Airport profit***: airport collaboration can improve the profit of the hub airport and the total profit of airports in the presence of air-HSR cooperation. However, the effect of airport collaboration on the transfer airport profit is ambiguous, regardless of air-HSR cooperation or not. Regardless of airport collaboration or not, air-HSR cooperation reduces the hub airport profit while increases the transfer airport profit.

4.2. Public regime with welfare-maximizing airports

When the hub airport and the transfer airport both aim to maximize social welfare, there are two scenarios, namely Scenario V without air-HSR cooperation, and Scenario VI with air-HSR cooperation. Referring to the definition of the social welfare in Section 3.3, the social welfare maximization problem for Scenario V can be expressed as

$$\begin{aligned}\max_{w^h, w^t} SW_V(w^h, w^t) = &\beta_{OD}(Q^a + q_k^c) - \frac{1}{2}\left(b(Q^a)^2 + b(q_k^c)^2 + 2\lambda Q^a q_k^c\right) - \sum_{i=1}^{N} \rho_i^a q_i^a - \rho_k^c q_k^c \\ &+ \beta_{TD} q^R - \frac{b}{2}(q^R)^2 - \rho^R q^R + \sum_{i=1}^{N} \pi_i^a + \pi_k^a + \pi_{HSR} + \Phi^h + \Phi^t,\end{aligned} \tag{50}$$

where π_k^a is the profit of airline *k*, and π_{HSR} is the profit of the HSR operator. For Scenario V, the expressions for the passenger volume and fares are identical to those for Scenario II.

For Scenario VI with the integration of airline *k* and the HSR, the social welfare maximization model can be expressed as

$$\begin{aligned}\max_{w^h, w^t} SW_{VI}(w^h, w^t) = &\beta_{OD}(Q^a + q_k^c) - \frac{1}{2}\left(b(Q^a)^2 + b(q_k^c)^2 + 2\lambda Q^a q_k^c\right) - \sum_{i=1}^{N} \rho_i^a q_i^a - \rho_k^c q_k^c \\ &+ \beta_{TD} q^R - \frac{b}{2}(q^R)^2 - \rho^R q^R + \sum_{i=1}^{N} \pi_i^a + \pi^c + \Phi^h + \Phi^t - C_F,\end{aligned} \tag{51}$$

where π^c is the total profit of airline *k* and the HSR operator. In Scenario VI, the expressions for the passenger volume and the fares are identical to those for Scenario IV.

Substituting related expressions into Eqs. (50) and (51), the social welfare maximization problems for Scenarios V and VI can respectively be rewritten as

$$\max_{w^h, w^t} SW_V(w^h, w^t) = \beta^a Q_V^a - \left(\frac{b}{2} + \theta\right)(Q_V^a)^2 + (\beta^c - c^R) q_{k,V}^c - \frac{b}{2}(q_{k,V}^c)^2 - \lambda Q_V^a q_{k,V}^c + \beta^R q_V^R - \frac{b}{2}(q_V^R)^2, \text{ and} \tag{52}$$

$$\max_{w^h, w^t} SW_{VI}(w^h, w^t) = \beta^a Q_{VI}^a - \left(\frac{b}{2} + \theta\right)(Q_{VI}^a)^2 + (\beta^c - c^R) q_{k,VI}^c - \frac{b}{2}(q_{VI}^c)^2 - \lambda Q_{VI}^a q_{k,VI}^c + \beta^R q_{VI}^R - \frac{b}{2}(q_{VI}^R)^2 - C_F. \tag{53}$$

From the first-order optimality conditions, one can derive the optimal airport charges and the associated passenger outputs for Scenarios V and VI as

$$
\begin{cases}
w_V^{h(**)} = \dfrac{\left(b-(N-1)\theta\right)\left(-5b\beta^a + 4\lambda(\beta^c - c^R) - \lambda\beta^R\right)}{N\left(5b(b+2\theta)-4\lambda^2\right)}, \\[2ex]
w_V^{t(**)} = \dfrac{5b\lambda\beta^a - 5b(b+2\theta)(\beta^c - c^R) + \lambda^2\beta^R}{5b(b+2\theta)-4\lambda^2}, \\[2ex]
q_{i,V}^{a(**)} = \dfrac{5b\beta^a - 4\lambda(\beta^c - c^R) + \lambda\beta^R}{N\left(5b(b+2\theta)-4\lambda^2\right)},\ \forall i = 1,2,\ldots,N, \\[2ex]
q_{k,V}^{c(**)} = \dfrac{-4\lambda\beta^a + 4(b+2\theta)(\beta^c - c^R) - (b+2\theta)\beta^R}{5b(b+2\theta)-4\lambda^2}, \\[2ex]
q_V^{R(**)} = \dfrac{2b\lambda\beta^a - 2b(b+2\theta)(\beta^c - c^R) + \left(3b(b+2\theta)-2\lambda^2\right)\beta^R}{b\left(5b(b+2\theta)-4\lambda^2\right)}.
\end{cases}
\tag{54}
$$

$$
\begin{cases}
w_{VI}^{h(**)} = \dfrac{\left(b-(N-1)\theta\right)\left(-b\beta^a + \lambda(\beta^c - c^R)\right)}{N\left(b(b+2\theta)-\lambda^2\right)}, \\[2ex]
w_{VI}^{t(**)} = \dfrac{b\left(\lambda\beta^a - (b+2\theta)(\beta^c - c^R)\right)}{b(b+2\theta)-\lambda^2}, \\[2ex]
q_{i,VI}^{a(**)} = \dfrac{b\beta^a - \lambda(\beta^c - c^R)}{N\left(b(b+2\theta)-\lambda^2\right)},\ \forall i = 1,2,\ldots,N, \\[2ex]
q_{k,VI}^{c(**)} = \dfrac{-\lambda\beta^a + (b+2\theta)(\beta^c - c^R)}{b(b+2\theta)-\lambda^2}, \\[2ex]
q_{VI}^{R(**)} = \dfrac{\beta^R}{2b}.
\end{cases}
\tag{55}
$$

Table 5 The effects of the air-HSR cooperation under the public regime.

Solution	**Scenario V vs VI**
Airport charge of hub airport	$w_V^{h(**)} > w_{VI}^{h(**)} > 0$ (if $N > 1 + b/\theta$) $0 > w_V^{h(**)} > w_{VI}^{h(**)}$ (if $N < 1 + b/\theta$)
Airport charge of transfer airport	$0 > w_V^{t(**)} > w_{VI}^{t(**)}$
Passenger output on direct air route	$q_{i,V}^{a(**)} > q_{i,VI}^{a(**)}$
Passenger output on air-HSR route	$q_{k,V}^{c(**)} < q_{k,VI}^{c(**)}$
Passenger output on HSR route	$q_{k,V}^{c(**)} + q_V^{R(**)} < q_{k,VI}^{c(**)} + q_{VI}^{R(**)}$
Passenger output on pure HSR market	$q_V^{R(**)} < q_{VI}^{R(**)}$

Comparing the results with and without air-HSR integration, we obtain Table 5 and the proposition below.

Proposition 6. Under the public regime when airports aim to maximize social welfare

(i) The cooperation of the entrant airline and the HSR operator in providing air-HSR service leads to decreased passenger output on the direct air route but increased passenger output on the air-HSR route.

(ii) The hub airport charge may be either positive or negative (i.e., a charge or a subsidy). If $N > 1 + b/\theta$, the hub airport charge is positive and will be reduced in the case of air-HSR integration. If $N < 1 + b/\theta$, the hub airport subsidizes the airlines on the direct route, and the air-HSR cooperation further raises the subsidy.

(iii) The transfer airport's charge is always negative (i.e., a subsidy) and the air-HSR cooperation will lead to a higher subsidy to the entrant airline provided by the transfer airport.

Proposition 6 offers some important policy implications, especially for airports under public/government control. First, the air-HSR cooperation shifts passenger volume from the hub airport to the transfer airport, thus alleviating the hub airport congestion. Second, from Proposition 6 (ii), the sign of the hub airport charge and the effect of the air-HSR cooperation on that charge depend on the number of competing airlines on the direct air route. When $N > 1 + b/\theta$, there is significant airline competition on the direct air route, which leads to strongly competitive air services and high passenger volume. It is welfare-enhancing for the hub airport to increase its charge to control passenger volume and congestion. With the air-HSR service introduced, some passengers are shifted to the transfer airport, allowing the hub airport to reduce its charge with reduced passenger volume. The situation reverses when $N < 1 + b/\theta$. This is an important result. Government subsidy is a sensitive issue. When the transfer airport subsidizes the air-HSR services, there can be significant anti-trust concerns over the fairness of competition between the direct air services and the air-HSR option. Our analytical results suggest that such a subsidy can be welfare-enhancing, which benefits passengers on both the direct route using air services (in terms of reduced congestion) as well as those on transfer route using the air-HSR transport option (in terms of reduced/subsidized total cost). Third, Proposition 6 (iii) indicates that under the public regime, if the hub and transfer airports in the MAS cooperate with each other, then the transfer airport should always subsidize the entrant airline on the air-HSR route, no matter with or without air-HSR cooperation. However, the air-HSR cooperation will enhance such kind of subsidy.

4.3. Comparison between the private regime and the public regime

In this subsection, we compare the equilibrium outcomes under the private and public regimes. Some notable results are summarized as follows.

Summary 2. If the hub airport collaborates with the transfer airport,

(i) Airport charges under the private regime are always higher than those under the public regime. Under the private regime, the air-HSR cooperation does not change the hub airport charge. However, under the public regime, the air-HSR cooperation would lower the hub airport charge or increase the subsidy from the hub airport to the airlines providing the direct air services. Besides, the air-HSR cooperation will increase the transfer airport charge (under the private regime) or the subsidy from the transfer airport to the airline on the air-HSR route (under the public regime).

(ii) The air-HSR cooperation reduces the passenger output on the direct air route, but increases the passenger outputs for both the air-HSR mode and the pure HSR mode, regardless of the airport regulatory regime.

(iii) For profit-maximizing airports, the air-HSR cooperation is beneficial for the whole airport system in terms of the total airport profit, although it reduces the operation profit of the hub airport. When airports aim for welfare-maximization, the effect of the air-HSR cooperation on the social welfare is ambiguous.

5. Model applications

In this section, we apply the proposed models to the Shanghai-Beijing market, which is one of the busiest inter-city transport markets in China. The distance between the two cities is about 1178 km. HSR service was first introduced in 2011, and eight airlines operated with similar services on the direct air route, taking more than 2 hours. After the HSR service between Shijiazhuang and Beijing was put into operation 2012, an airline (i.e., Spring Airlines) started to offer an air-HSR inter-modal service on the Shanghai-Shijiazhuang-Beijing route, using the SJW (airport in Shijiazhuang) as the transfer airport. In reality, the line-haul travel time of the flights on the Shanghai-Shijiazhuang leg and the line-haul travel time of trains on the Shijiazhuang-Beijing leg are about 115 minutes and 75 minutes, respectively (Li and Sheng, 2016). The total connecting time from alighting the plane at the airport to boarding train at the HSR station is assumed to be 60 minutes. The total en-route journey time of air-HSR mode is thus 250 minutes. The monetary travel cost Δc between airport and HSR station is set to be zero, because the SJW airport and the HSR station are located at the same building complex. According to Xia et al. (2019), the size of Shanghai-Beijing aviation market can be calibrated by examining the daily schedule of the direct flights from Shanghai to Beijing. There are a total of 58 direct flights flying from Shanghai to Beijing on a typical weekday. The capacities of different aircraft for the market are shown in Table 6, which were identified from the previous literature (Swan and Adler, 2006; Xia et al., 2019) and the online resources. Then, based on the method of Xia et al. (2019) and the seat capacity, we can calibrate the market size parameter $\beta_{OD} = 19373$. The market size parameter of the local pure HSR market (i.e., OD HSR travel between transfer airport city Shijiazhuang to hub airport city Beijing) can be similarly calibrated as $\beta_{TD} = 9072$. The marginal operating costs of airlines and the HSR operator are assumed to be RMB200 and RMB150 per person, respectively (Yang and Zhang, 2012).[6] The passengers' value of time is assumed to be RMB30 per hour and the substitution parameter b is assumed to be 1.0. The values of the model parameters are listed in Table 7. In the following, we will examine the effects of the airport congestion parameter $\theta \in [0,1]$ and the substitution parameter $\lambda \in [0,1]$ through carrying out the sensitivity analysis.

Table 6 Aircraft deployment for Shanghai-Beijing market.

Aircraft type	B747	B787	B777	B737	A320	A330	A321	A350
Number of flights	4	4	8	11	2	21	4	4
Capacity (number of seats)	429	250	385	162	150	268	183	315

Table 7 Values of the model parameters.

Parameter	**Description**	**Baseline value**
β_{OD}	Market size of Shanghai-Beijing market (persons/day)	19373
β_{TD}	Market size of local HSR market (persons/day)	9072
α	Passengers' value of time (RMB/h)	30
c^a	Marginal operating cost of airline (RMB/person)	200
c^R	Marginal operating cost of HSR (RMB/person)	150
t^a	Line-haul time of direct air mode (minutes)	140
t^c	Line-haul travel time of air-HSR mode (minutes)	190
t^R	Line-haul travel time of HSR mode (minutes)	75
Δt	Connecting time between transfer airport and HSR station (minutes)	60
Δc	Monetary travel cost between transfer airport and HSR station (RMB/person)	0
N	Number of competing airlines on direct air route	8
b	Slope of demand function	1.0

[6] "RMB" stands for the Chinese currency "Renminbi". US$1 was about RMB6.52 as of Jan 1, 2021.

We first look at the private regime of profit-maximizing airports, which contains four scenarios (i.e., Scenarios I, II, III, and IV). Fig. 5 shows the relationships among Scenarios I, II, III, and IV in terms of the total airport profit for different combinations of λ and θ. It can be observed that there are two indifference curves that divide the whole (λ, θ) plane into three regions (i.e., A, B, and C). The indifference curve between regions A and B corresponds to a situation of $\Phi_{III}^{(*)} = \Phi_{II}^{(*)}$, whereas the indifference curve between regions B and C corresponds to a situation of $\Phi_{III}^{(*)} = \Phi_{I}^{(*)}$. Fig. 5 confirms that Scenario IV would lead to the highest total airport profit, and the total airport profit of Scenario I is lower than that of Scenario II (i.e., $\Phi_{I}^{(*)} < \Phi_{II}^{(*)}$). The intuition is clear: collaboration between the hub and transfer airports would allow them to secure higher total airport profit.

Fig. 5 also shows that when airports collaborate, air-HSR cooperation increases the total airport profit (i.e., $\Phi_{II}^{(*)} < \Phi_{IV}^{(*)}$). This result does not always hold if airport does not collaborate. Specifically, for regions A and B, air-HSR cooperation can indeed generate a higher total airport profit (i.e., $\Phi_{I}^{(*)} < \Phi_{III}^{(*)}$). However, for region C with a high substitution degree (i.e., a large λ value) and a low congestion cost level (i.e., a small θ value), the air-HSR cooperation reduces total airport profit or $\Phi_{I}^{(*)} > \Phi_{III}^{(*)}$. These results suggest that airports in a region prefer collaboration, but they prefer to have more competition in the downstream airline markets (i.e. by collaborating/supporting the air-HSR service).

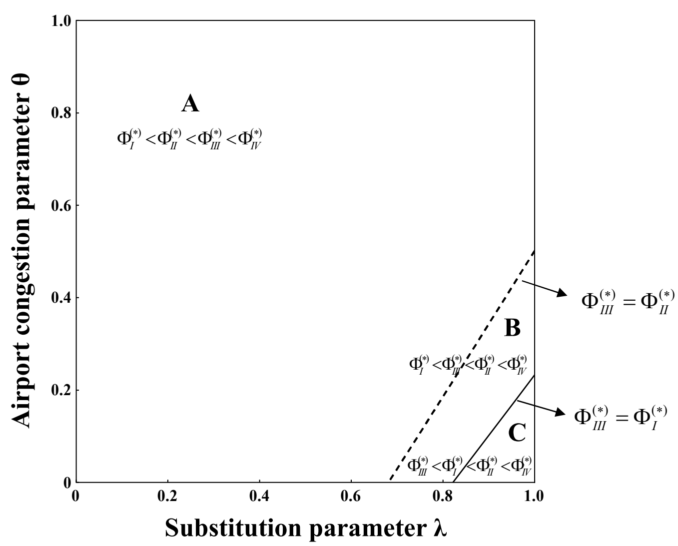
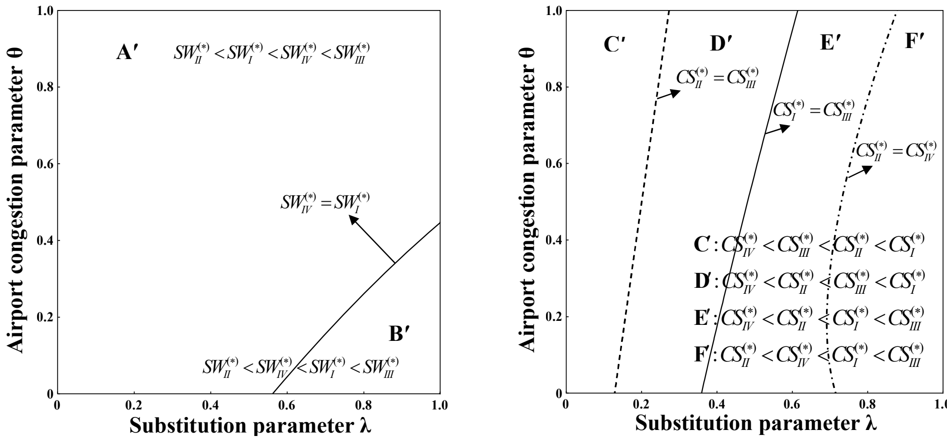


Fig. 5. Effects of λ and θ on total airport profit under private regime.



(a) (b)

Fig. 6. Effects of λ and θ on total social welfare and consumer surplus under private regime: (a) social welfare; (b) consumer surplus.

Next, we discuss the total social welfare and consumer surplus for different combinations of λ and θ for the case of the private regime. The consumer surplus is defined below for the scenarios with and without air-HSR cooperation:

$$CS = \begin{cases} \beta_{OD}(Q^a + q_k^c) - \frac{1}{2}\left(b(Q^a)^2 + b(q_k^c)^2 + 2\lambda Q^a q_k^c\right) - \sum_{i=1}^{N}\rho_i^a q_i^a - \rho_k^c q_k^c + \beta_{TD} q^R - \frac{b}{2}(q^R)^2 - \rho^R q^R, & \text{for air-HSR non-cooperation,} \\ \beta_{OD}(Q^a + q_k^c) - \frac{1}{2}\left(b(Q^a)^2 + b(\rho_k^c)^2 + 2\lambda Q^a \rho_k^c\right) - \sum_{i=1}^{N}\rho_i^a q_i^a - \rho_k^c q_k^c + \beta_{TD} q^R - \frac{b}{2}(q^R)^2 - \rho^R q^R, & \text{for air-HSR cooperation.} \end{cases} \quad (56)$$

Fig. 6 shows the effects of λ and θ on the social welfare and consumer surplus under private regime. It can be observed in Fig. 6a that Scenario III (air-HSR cooperation but airport non-collaboration) can lead to the highest total social welfare, while Scenario II (airport collaboration but air-HSR non-cooperation) leads to the lowest total social welfare; full cooperation (Scenario IV) must not generate high social welfare, and full non-cooperation must not induce low social welfare. This means that the airport collaboration and the air-HSR cooperation have reverse impacts on the society in terms of social welfare. The airport collaboration would decrease social welfare, and such a decrease sometimes exceeds the increase in social welfare caused by the air-HSR cooperation. For example, in region B′ the social welfare of Scenario IV is lower than that of Scenario I. The intuition is clear: on the one hand, cooperation between the entrant airline and the HSR operator removes double-marginalization problem and makes the inter-modal service more competitive against direct air service. However, collaboration between two profit maximizing airports in a region will significantly reduce competition in the airport market and the downstream airline market, which reduces social welfare even though congestion at hub airport is reduced with traffic shifting to transfer airport.

However, high social welfare does not mean high consumer surplus. As shown in Fig. 6b, in region C′, D′ and E′, the rankings of the scenarios in terms of consumer surplus are different from those in terms of social welfare. For example, in region C′, the consumer surplus of Scenario IV is the lowest, but its social welfare ranks the second. However, if the substitution level is high enough (i.e., in region F′), the rankings in terms of consumer surplus and in terms of social welfare may be the same.

We now look at the case of the public regime in which airports maximize social welfare. Fig. 7 shows the contours of $SW_{VI}^{(**)} - SW_{V}^{(**)}$ and $CS_{VI}^{(**)} - CS_{V}^{(**)}$, which are respectively the difference of social welfare and the difference of consumer surplus of Scenario VI (air-HSR integration) and Scenario V (air-HSR provided by independent airline and HSR operator). It can be found that the social welfare of Scenario VI is always higher than that of Scenario V for any $\theta \in [0,1]$ and any $\lambda \in [0,1]$. That is, when airports maximize the social welfare, the air-HSR integration always improves the total social welfare.

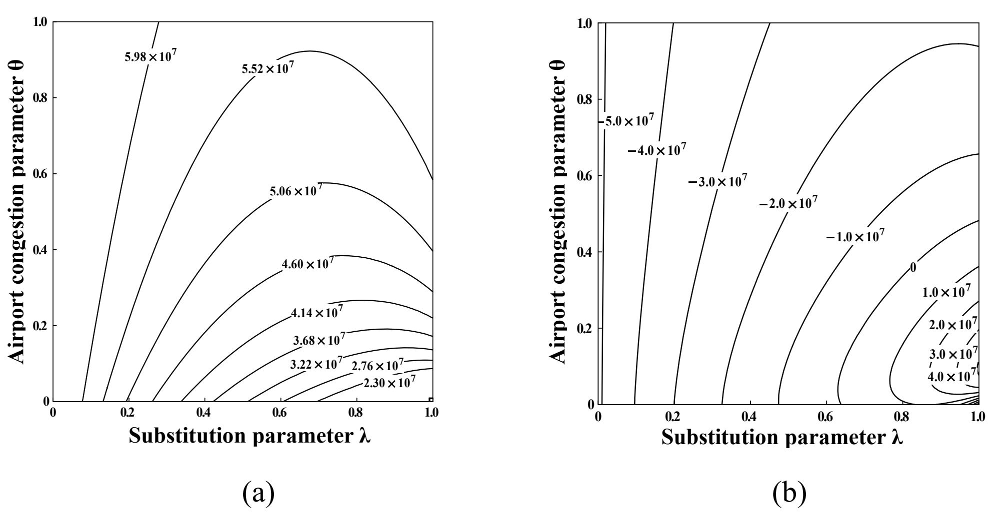


Fig. 7. Comparison of social welfare and consumer surplus of Scenarios VI and V under public regime: (a) difference of social welfare; (b) difference of consumer surplus.

Fig. 7a also shows that for a given substitution level λ, as the airport congestion level θ increases, the welfare difference $SW_{VI}^{(**)} - SW_{V}^{(**)}$ enlarges. Intuitively when the hub airport is very congested, the air-HSR integration can play a more important role in enhancing the social welfare by shifting traffic to the transfer airport. However, again the high social welfare does not mean high consumer surplus. For example, in the bottom right of Fig. 7b, the consumer surplus of Scenario VI is higher than that of Scenario V. However, the reverse pattern is observed in the rest of the plane. The observation suggests that if the substitution level λ is not high enough and the congestion level θ is not low enough, the air-HSR cooperation may harm the consumer surplus.

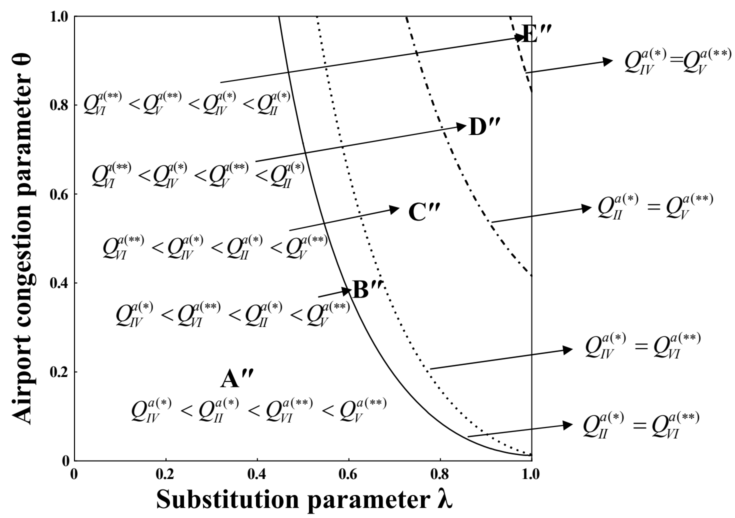


Fig. 8. Passenger outputs at hub airport under different airport regulatory regimes.

Finally, we examine the effects of the airport regimes on the congestion level of the hub airport through comparing the passenger outputs (i.e., $Q^a = \sum_{i=1}^{n} q_i^a$) under private regime ($Q_{II}^{a(*)}$ and $Q_{IV}^{a(*)}$) and public regime ($Q_V^{a(**)}$ and $Q_{VI}^{a(**)}$), as shown in Fig. 8. It can be seen that $Q_{IV}^{a(*)} < Q_{II}^{a(*)}$ and $Q_{VI}^{a(**)} < Q_V^{a(**)}$ always hold, implying that the air-HSR cooperation would lead to fewer passenger volume at the hub airport (regardless of the public or private regime), and thus lower hub airport congestion level. There are four indifference curves that divide the whole (λ, θ) plane into five regions: A″, B″, C″, D″ and E″. For region A″, the passenger output at the hub airport (or the hub airport congestion level) under the public regime ($Q_V^{a(**)}$ and $Q_{VI}^{a(**)}$) would be higher than that under the private regime ($Q_{II}^{a(*)}$ and $Q_{IV}^{a(*)}$), regardless of air-HSR cooperation or not. For region E″, the result is reversed, i.e., the hub airport congestion level under the private regime would be higher than that under the public regime. For other regions (i.e., B″, C″ and D″), the comparison of the hub airport congestion under the public and private regimes depends on the air-HSR cooperation. For example, for region C″, with the air-HSR cooperation, the hub airport congestion level under the public regime is lower than that under the private regime (i.e., $Q_{VI}^{a(**)} < Q_{IV}^{a(*)}$). However, the result is reversed when there is no air-HSR cooperation (i.e., $Q_{II}^{a(*)} < Q_{V}^{a(**)}$). As the combination of λ and θ changes from region A″ to region E″ (i.e., λ and/or θ increase), the passenger output (and thus the congestion level) at the hub airport under the public regime decreases. This means that the public regime is helpful for alleviation of the hub airport congestion for large values of λ and/or θ. Overall, however, the public regime does not always reduce hub airport congestion.

6. Extensions

6.1. Extension 1: Incorporating direct HSR service

For mathematical tractability, in the previous sections we consider a transport network consisting of two markets: one is the OD market with two alternative travel modes, namely direct air and combined air-HSR service; and the other is the pure HSR market between transfer airport and destination city. In this section, we further incorporate the direct HSR service in the OD market to compete with direct air and air-HSR service. The OD pair of Shanghai-Beijing can serve as a typical example: the en-route journey time is about 270-390 minutes by direct HSR, about 140 minutes by direct air mode, and about 250 minutes by the air-HSR mode. Although the en-route journey time by direct HSR mode is longer than that by other two modes, it needs less access time to Hongqiao HSR station and less waiting time at the HSR station, and no transfer. Consequently, direct HSR mode is a competitive substitute for the direct air and the air-HSR mode. Following the approach presented in the previous sections, one can easily solve the vertical-structure model with the incorporation of the additional direct HSR mode (referring to Fig. 3b), as follows.

In the vertical-structure model, the passenger's mode choice behavior is closely related to the full prices of alternative modes. The full price of the direct HSR mode (represented as ρ^{DR}) includes the travel time cost and the HSR ticket price, expressed as

$$\rho^{DR} = \alpha t^{DR} + \tau^{DR}, \tag{57}$$

where superscript "*DR*" represents the direct HSR mode. t^{DR} is the line-haul travel time and τ^{DR} is the ticket price of the direct HSR service.

The linear inverse demand functions for different travel modes can be defined as

$$\begin{cases} \rho_i^a = \beta_{OD} - b\sum_{i=1}^{N} q_i^a - \lambda q_k^c - \lambda q^{DR}, \ \forall i = 1, 2, \cdots, N, \\ \rho_k^c = \beta_{OD} - \lambda \sum_{i=1}^{N} q_i^a - b q_k^c - \lambda q^{DR}, \\ \rho^{DR} = \beta_{OD} - \lambda \sum_{i=1}^{N} q_i^a - \lambda q_k^c - b q^{DR}, \\ \rho^R = \beta_{TD} - b q^R, \end{cases} \tag{58}$$

where q^{DR} is the passenger output on the direct HSR route of the OD pair concerned.

The competitive behavior of HSR and airlines depends on whether the entrant airline cooperates with the HSR company or not. If the entrant airline does not cooperate with the HSR company, then the associated profit maximization problems can be formulated as

$$\begin{cases} \max\limits_{q_i^a} \pi_i^a(q_i^a) = (\tau_i^a - c^a - w^h) q_i^a, \ \forall i = 1, 2, \cdots, N, \\ \max\limits_{q_k^c} \pi_k^a(q_k^c) = (\tau_k^a - c^a - w^t) q_k^c, \\ \max\limits_{q^{DR}, q^R} \pi^R(q^{DR}, q^R) = (\tau^{DR} - c^{DR}) q^{DR} + (\tau^R - c^R)(q^R + q_k^c). \end{cases} \tag{59}$$

where c^{DR} is the marginal operating cost per passenger for the direct HSR mode of the OD market.

If the entrant airline cooperates with the HSR firm for providing the air-HSR service, then the associated profit maximization problems are

$$\begin{cases} \max\limits_{q_i^a} \pi_i^a(q_i^a) = (\tau_i^a - c^a - w^h) q_i^a, \ \forall i = 1, 2, \cdots, N, \\ \max\limits_{q_k^c, q^R} \pi^c(q_k^c, q^R) = (\tau_k^c - c^a - w^t - c^R) q^c + (\tau^R - c^R) q^R - C_F, \\ \max\limits_{q^{DR}} \pi^{DR}(q^{DR}) = (\tau^{DR} - c^{DR}) q^{DR}, \end{cases} \tag{60}$$

where π^c is the total profit of the air-HSR operator, and π^{DR} is the profit of the direct HSR.

Based on the passengers' mode choices and carriers' profit maximization formulations (i.e., Eqs. (57)-(60) and Eqs. (1), (18) and (22)), one can obtain the passenger output solutions without and with air-HSR cooperation, expressed as

$$\begin{cases} q^a_{i,I} = q^a_{i,II} = q^a_{i,V} = \dfrac{2(5b^2-\lambda^2)(\beta^a - w^h) - \lambda(2b-\lambda)\left(2(\beta^c - w^t - c^R) - \beta^R\right) - \lambda(5b-2\lambda)\beta^{DR}}{2D(5b^2-\lambda^2) - N\lambda^2(9b-4\lambda)}, \ \forall i = 1,2,\ldots,N, \\ q^c_{k,I} = q^c_{k,II} = q^c_{k,V} = \dfrac{-2N\lambda(2b-\lambda)(\beta^a - w^h) + (2bD - N\lambda^2)\left(2(\beta^c - w^t - c^R) - \beta^R\right) - 2\lambda(D - N\lambda)\beta^{DR}}{2D(5b^2-\lambda^2) - N\lambda^2(9b-4\lambda)}, \\ q^{DR}_{I} = q^{DR}_{II} = q^{DR}_{V} = \dfrac{-N\lambda(5b-2\lambda)(\beta^a - w^h) - \lambda(D-N\lambda)\left(2(\beta^c - w^t - c^R) - \beta^R\right) + (5bD - 2N\lambda^2)\beta^{DR}}{2D(5b^2-\lambda^2) - N\lambda^2(9b-4\lambda)}, \\ q^R_I = q^R_{II} = q^R_V = \dfrac{\beta^R}{2b} + \dfrac{2bN\lambda(2b-\lambda)(\beta^a - w^h) - b(2bD - N\lambda^2)\left(2(\beta^c - w^t - c^R) - \beta^R\right) + 2b\lambda(D-N\lambda)\beta^{DR}}{2b\left(2D(5b^2-\lambda^2) - N\lambda^2(9b-4\lambda)\right)}. \end{cases} \tag{61}$$

$$\begin{cases} q^a_{i,III} = q^a_{i,IV} = q^a_{i,VI} = \dfrac{(2b+\lambda)(\beta^a - w^h) - \lambda(\beta^c - w^t - c^R) - \lambda\beta^{DR}}{D(2b+\lambda) - 2N\lambda^2}, \ \forall i = 1,2,\ldots,N, \\ q^c_{k,III} = q^c_{k,IV} = q^c_{k,VI} = \dfrac{-N\lambda(2b-\lambda)(\beta^a - w^h) + (2bD - N\lambda^2)(\beta^c - w^t - c^R) - \lambda(D-N\lambda)\beta^{DR}}{D(4b^2-\lambda^2) - 2N\lambda^2(2b-\lambda)}, \\ q^{DR}_{III} = q^{DR}_{IV} = q^{DR}_{VI} = \dfrac{-N\lambda(2b-\lambda)(\beta^a - w^h) - \lambda(D-N\lambda)(\beta^c - w^t - c^R) + (2bD - N\lambda^2)\beta^{DR}}{D(4b^2-\lambda^2) - 2N\lambda^2(2b-\lambda)}, \\ q^R_{III} = q^R_{IV} = q^R_{VI} = \dfrac{\beta^R}{2b}, \end{cases} \tag{62}$$

where $\beta^{DR} = \beta_{OD} - \alpha t^{DR} - c^{DR}$ denotes the welfare of a representative passenger using the direct HSR service of the OD pair concerned.

The airport charge decision models after incorporating the additional direct HSR mode are similar to those before incorporating the direct HSR mode. Substituting Eqs. (61) and (62) into the airport charge decision models, one can derive the optimal airport charge solutions under the private and public regulatory regimes, as shown in Appendix A. For saving space, the detailed derivations are omitted here, but are available from authors on request.

Again, we apply the model to the Shanghai-Beijing market. The parameter values of the model are the same as those in Table 7, except for the line-haul journey time t^{DR} and the marginal operating cost of the HSR mode. In reality, the line-haul journey time between Shanghai and Beijing changes between 270 minutes and 390 minutes. We thus set the line-haul journey time t^{DR} as its average value, i.e., 330 minutes. The marginal operating cost c^{DR} can be valued with reference to c^R.

Fig. 9 shows the relationships among Scenarios I to IV in terms of the total airport profit for different combinations of λ and θ. The indifference curves divide the whole (λ, θ) plane into four regions (i.e., A, B, C and D). Fig. 9 is similar to Fig. 5a, but with two differences. One is the change in the region size. Specifically, the size of region A enlarges, whereas those of regions B and C shrink. This means that after the direct HSR mode is introduced in

Shanghai-Beijing market, the air-HSR cooperation may improve the total airport profit for more combinations of λ and θ. The other is addition of region D, in which the total airport profit for Scenario II becomes higher than that for Scenario IV, which is reversed in Fig. 5a. This means that after introducing the direct HSR mode, the air-HSR cooperation may decrease the total airport profit for the hub and transfer airport collaborative case if λ is enough large and θ is enough small.

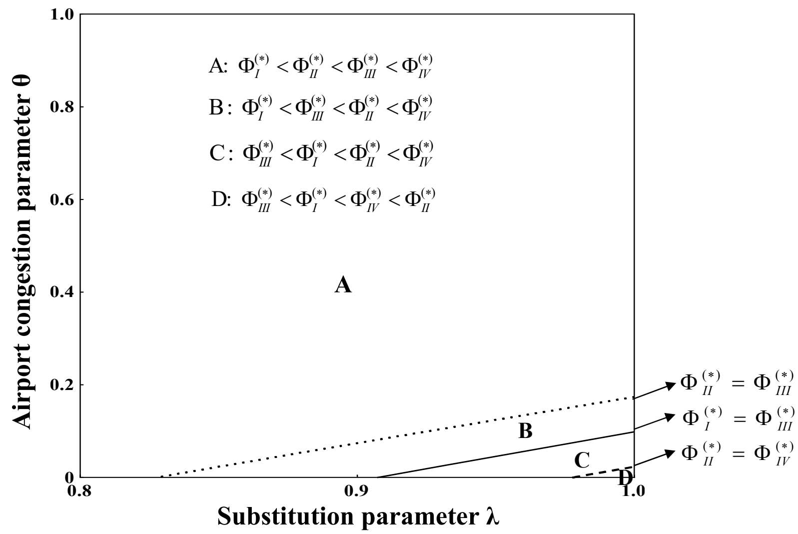


Fig. 9. Effects of λ and θ on total airport profit under private regime.

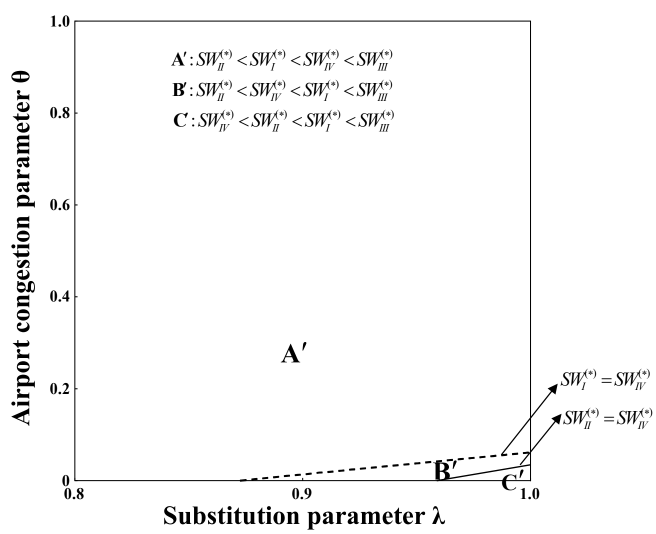


Fig. 10. Effects of λ and θ on total social welfare under private regime.

Fig. 10 shows the effects of λ and θ on the total social welfare under the private regime.

Comparing Figs. 6a and 10, it can be found that there is an additional region C′, in which the total social welfare of Scenario II becomes higher than that of Scenario IV. This means that after the direct HSR mode is available for a long-distance journey, air-HSR cooperation may also decrease the total social welfare when the hub airport collaborates with the transfer airport.

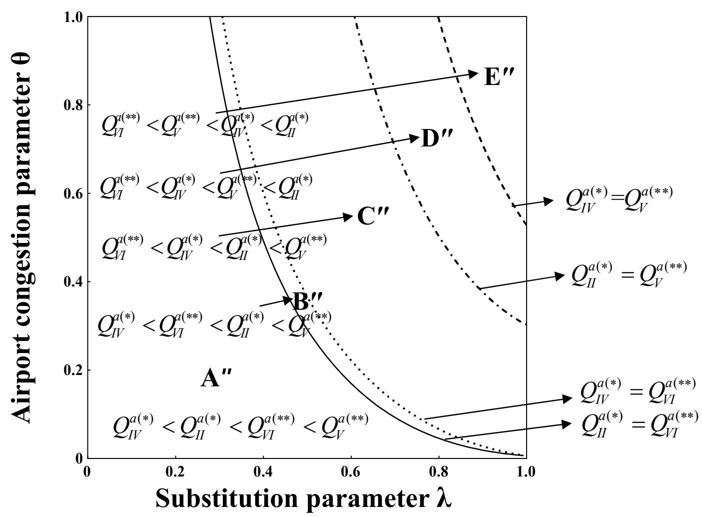


Fig. 11. Passenger outputs at hub airport under different airport regulatory regimes.

Fig. 11 indicates the effects of airport regimes on the congestion level of the hub airport. It can be observed that compared to Fig. 8, all the indifference curves in Fig. 11 move towards the bottom left. Such observations suggest that stronger competition between an OD market due to the additional direct HSR mode can lead to a lower passenger volume at the hub airport under the public regime than under the private regime for more combinations of λ and θ.

6.2. Extension 2: Incorporating heterogeneous airlines and revenue sharing

In this section, the proposed models in the previous sections are further extended to consider airline heterogeneity and the revenue-sharing arrangement between airline(s) and the HSR firm. Suppose that the HSR firm has market power, and thus some or all of the airlines on the air-HSR route seek cooperation with the HSR firm. Once the HSR firm agrees to cooperate with one or more airlines, passengers can purchase integrated ticket for the whole air-HSR service from the cooperating airline, and each cooperating airline shares part of the revenue from the integrated ticket price with the HSR firm. In this paper, it is assumed that the HSR firm has the market power, and thus the revenue-sharing amounts are determined by the HSR firm. This section aims to identify the merits of the HSR cooperation with some or all airlines, and compare the profit and revenue sharing outcomes.

Let M be the number of airlines on the air-HSR route, and $m\ (m \le M)$ be the number of airlines cooperating with the HSR firm on the air-HSR route. Without loss of generality, let $k\ (k = 1, 2, \ldots, m)$ be a cooperating airline with the HRS firm. The full travel costs for different modes can be expressed as

$$\begin{cases} \rho_i^a = \alpha t_i^a + D(F^a, K) + \tau_i^a,\ i = 1, 2, \ldots, N,\ \text{for direct air}, \\ \rho_k^c = \alpha(t_k^c + \Delta t_k^c) + \Delta c_k^c + \tau_k^c,\ k = 1, 2, \ldots, m,\ \text{for air-HSR cooperation}, \\ \rho_k^c = \alpha(t_k^c + \Delta t_k^c) + \Delta c_k^c + \tau_k^a + \tau^R,\ k = m+1, m+2, \ldots, M, \text{for air-HSR non-cooperation}, \\ \rho^{DR} = \alpha t^{DR} + \tau^{DR},\ \text{for direct HSR route}, \\ \rho^R = \alpha t^R + \tau^R,\ \text{for local HSR market}, \end{cases} \tag{63}$$

where ρ_k^c denotes the full travel cost of the air-HSR mode, which is provided by airline k and the HSR firm. t_k^c and τ_k^a are, respectively, the en-route travel time of the air-HSR mode and the airfare of airline k when it does not cooperate with the HSR firm. τ_k^c denotes the integrated ticket price of the air-HSR service, paid by passengers to airline $k\ (k = 1, 2, \ldots, m)$. Δt_k^c and Δc_k^c are the time and monetary cost of transferring between the transfer airport and the HSR station, respectively.

Similar to Eq. (2), the congestion cost $D(F^a, K)$ at the hub airport can be calculated by

$$D(F^a, K) = \sum_{i=1}^{n} \theta_i q_i^a, \tag{64}$$

where $\theta_i = \hat{\theta} / K s_i$ can be regarded as the congestion cost that generated by airline i at the hub airport, and s_i is the average number of passengers per flight of airline i.

The linear inverse demand functions for different travel modes can be defined as

$$\begin{cases} \rho_i^a = \beta_{OD} - bq_i^a - \lambda \sum\limits_{j=1, i \neq j}^{N} q_j^a - \lambda \sum\limits_{k=1}^{M} q_k^c - \lambda q^{DR}, \ \forall i = 1,2,\cdots, N, \\ \rho_k^c = \beta_{OD} - \lambda \sum\limits_{i=1}^{N} q_i^a - bq_k^c - \lambda \sum\limits_{l=1, l \neq k}^{M} q_l^c - \lambda q^{DR}, \ \forall k = 1,2,\cdots, M, \\ \rho^{DR} = \beta_{OD} - \lambda \sum\limits_{i=1}^{N} q_i^a - \lambda \sum\limits_{k=1}^{M} q_k^c - bq^{DR}, \\ \rho^R = \beta_{TD} - bq^R. \end{cases} \tag{65}$$

Similar to the previous sections, one can formulate the multi-stage game models of airports, airlines, and passengers under the HRS cooperation with m airlines. For the sake of brevity, only profit-maximizing airports are considered here, and the corresponding models without and with airport collaboration are summarized in Table 8.

Table 8 Multi-stage game models without and with airport collaboration.

	Scenario III (airport non-collaboration)	**Scenario IV (airport collaboration)**
Airport charge decision model	$\begin{cases} \max\limits_{w^h} \ \Phi^h(w^h) = w^h \sum\limits_{i=1}^{N} q_i^a, \text{ for hub airport} \\ \max\limits_{w^t} \ \Phi^t(w^t) = w^t \sum\limits_{k=1}^{M} q_k^c, \text{ for transfer airport} \end{cases}$	$\max\limits_{w^h, w^t} \ \Phi(w^h, w^t) = w^h \sum\limits_{i=1}^{N} q_i^a + w^t \sum\limits_{k=1}^{M} q_k^c$
Revenue-sharing amount decision model of the HSR firm	$\max\limits_{r_1^c, r_2^c, \cdots, r_m^c} \pi_{HSR}(q^{DR}, q^R) = (\tau^{DR} - c^{DR}) q^{DR} + \sum\limits_{k=1}^{m} (r_k - c^R) q_k^c + \sum\limits_{k=m+1}^{M} (\tau^R - c^R)(q^R + q_k^c)$	
Decisions of airlines and HSR firm	Airlines on the direct air route: $\max\limits_{q_i^a} \pi_i^a(q_i^a) = (\tau_i^a - w^h - c_i^a) q_i^a, \ \forall i = 1,2,\cdots, N$ Airlines on the air-HSR route: $\begin{cases} \max\limits_{q_k^c} \pi_k^a(q_k^c) = (\tau_k^a - w^t - c_k^a) q_k^c, \ \forall k = 1,2,\cdots, m \\ \max\limits_{q_k^c} \pi_k^a(q_k^c) = (\tau_k^c - w^t - c_k^a - r_k) q_k^c, \ \forall k = m+1, m+2, \cdots, M \end{cases}$ The HSR firm: $\max\limits_{q^{DR}, q^R} \pi_{HSR}(q^{DR}, q^R) = (\tau^{DR} - c^{DR}) q^{DR} + \sum\limits_{k=1}^{m} (r_k - c^R) q_k^c + \sum\limits_{k=m+1}^{M} (\tau^R - c^R)(q^R + q_k^c)$	

Note: c_i^a and c_k^a are the marginal operating costs of airline i $(i = 1,2,\cdots, N)$ and airline k $(k = 1,2,\cdots, M)$, respectively. r_k is the amount of revenue-sharing of airline k $(k = 1,2,\cdots, m)$ and the HSR firm.

For general models presented in Table 8, the derivations of the model solutions are very complicated. Here, we consider a simple and representative case with two airlines (airlines i and j) on the direct air route and two airlines (airline k and l) on the air-HSR route, i.e., $N = M = 2$. With the air-HSR cooperation, there exist two possible cases: the HSR firm cooperates with only one airline (e.g., airline l) and the HSR firm cooperates with each of both airlines (e.g., airlines l and k). The corresponding network structure is shown in Fig. 13.

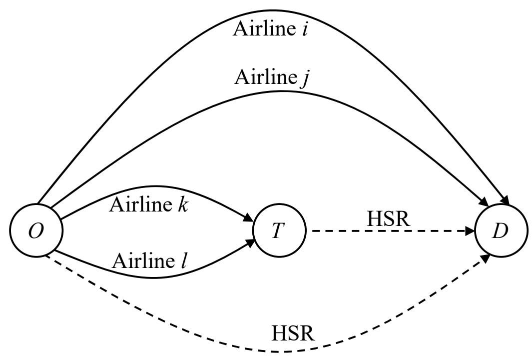


Fig. 13. A network with two airlines on direct air route and two airlines on air-HSR route.

According to the models in Table 8, one can derive the solutions for the case with two airlines (airlines *i* and *j*) on the direct air route and two airlines (airline *k* and *l*) on the air-HSR route. To save space, the detailed derivations are not presented here, but are available from the authors upon request.

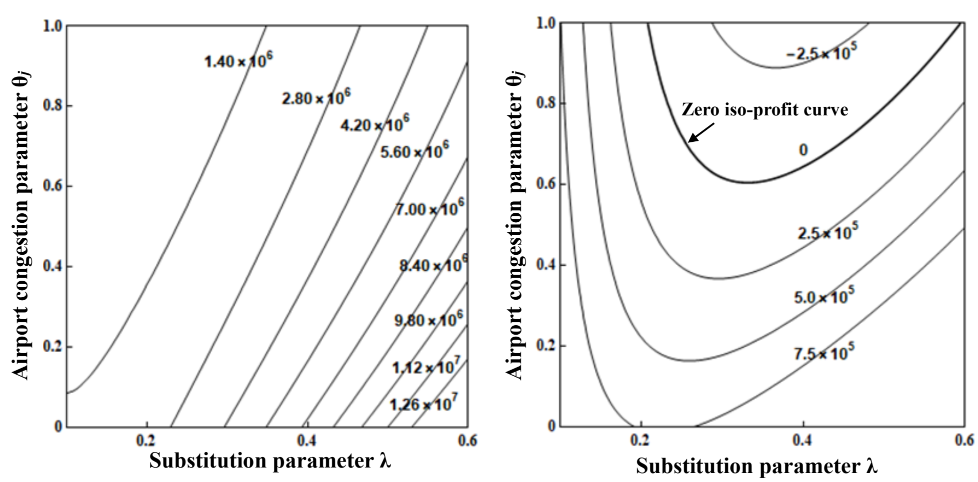
We apply the above models to the Shanghai-Beijing market again. The marginal operating costs of airlines *i*, *j*, *k* and *l* are, respectively, assumed to be RMB200/person, RMB230/person RMB200/person and RMB150/person. The values of the line-haul travel time for different transport modes, i.e., t_i^a, t_j^a, t_k^c and t_l^c, are 140, 140, 190 and 190 minutes, respectively. The congestion parameters θ_i and θ_j are set to 0.8, and the substitution parameter λ is set to 0.3. The values of other parameters are the same with those in Table 7 and Section 6.1.

Table 9 Comparison of solutions for HSR cooperation with one and two airlines.

		Scenario III (airport non-collaboration)		**Scenario IV (airport collaboration)**	
		One cooperating airline *l*	Two cooperating airlines *l* and *k*	One cooperating airline *l*	Two cooperating airlines *l* and *k*
Profit (RMB)	Airline *i*	1.73×10^7	1.82×10^7	1.56×10^7	1.78×10^7
	Airline *j*	1.75×10^7	1.83×10^7	1.58×10^7	1.80×10^7
	Airline *k*	1.64×10^7	2.04×10^7	1.39×10^7	1.92×10^7
	Airline *l*	2.64×10^7	2.10×10^7	2.21×10^7	1.99×10^7
	HSR	1.60×10^8	1.51×10^8	1.62×10^8	1.50×10^8
	MAS	4.44×10^7	4.58×10^7	4.61×10^7	4.59×10^7
Revenue-sharing ratio	(HSR, Airline *k*)	–	(40.88%, 59.12%)	–	(38.95%, 61.05%)
	(HSR, Airline *l*)	(49.7%, 50.3%)	(40.79%, 59.21%)	(41.29%, 58.71%)	(38.85%, 61.15%)

Note: The revenue-sharing ratio is a ratio of the revenue-sharing amount to the integrated ticket price per air-HSR passenger.

Table 9 reports the resultant profit and revenue-sharing ratio solutions when the HSR firm on the air-HSR route cooperates with only one airline and with each of the two airlines. Some main results are summarized as follows. (i) For the airport non-collaboration (Scenario III), the profit-maximizing airports prefer the HSR cooperation with each of the two airlines due to an increased total airport profit by RMB1.4×10^6 (from RMB4.44×10^7 to RMB4.58×10^7). However, for the airport collaboration (Scenario IV), the profit-maximizing airports prefer for the HSR cooperation with only one airline because its resultant total airport profit is RMB2.0×10^5 higher than that with two airlines. (ii) Regardless of airport collaboration or not, the HSR firm would like to cooperate with only one airline for maximizing its own profit. However, all airlines on the direct air routes prefer the HSR firm to cooperate with each of two airlines such that all of their own profits increase due to stronger competition between air-HSR services. The revenue-sharing ratio of each airline (or HSR) under the HSR cooperation with two airlines thus increases (or decreases), compared to the HSR cooperation with only one airline.



(a) (b)

Fig. 14. Effects of λ and θ_j on total airport profit with one or two cooperating airlines: (a) airport non-collaboration; (b) airport collaboration.

In the following, we examine the effects of the substitution parameter λ and the airport congestion parameters θ_i and θ_j using sensitivity analysis method. Fig. 14 shows the contour of the difference of the total airport profits under the HSR cooperation with one airline and with two airlines for different combinations of substitution parameter λ and congestion parameter θ_j when the other congestion parameter is fixed as $\theta_i = 0.8$. Fig. 14a plots the contour of the airport profit difference $\tilde{\Phi}_{III}^{(*)} - \Phi_{III}^{(*)}$ without airport cooperation, where $\Phi_{III}^{(*)}$ and $\tilde{\Phi}_{III}^{(*)}$ represent the resultant total airport profit with one and two cooperating airlines, respectively. It shows that the HSR cooperation with more airlines would improve the total airport profit under airport non-collaboration. However, under airport collaboration, a zero iso-profit curve (i.e., $\tilde{\Phi}_{IV}^{(*)} - \Phi_{IV}^{(*)} = 0$) divides the whole plane (λ, θ_j) into a positive and a negative region, as shown in Fig. 14b. Specifically, for the region below the zero iso-profit curve, the HSR cooperation with each of the two heterogeneous airlines is better than that with only one airline in terms of total airport profit. However, this result is reversed for the region above the zero iso-profit curve, i.e., the HSR cooperation with only one airline is a better scheme than that with each of the two airlines.

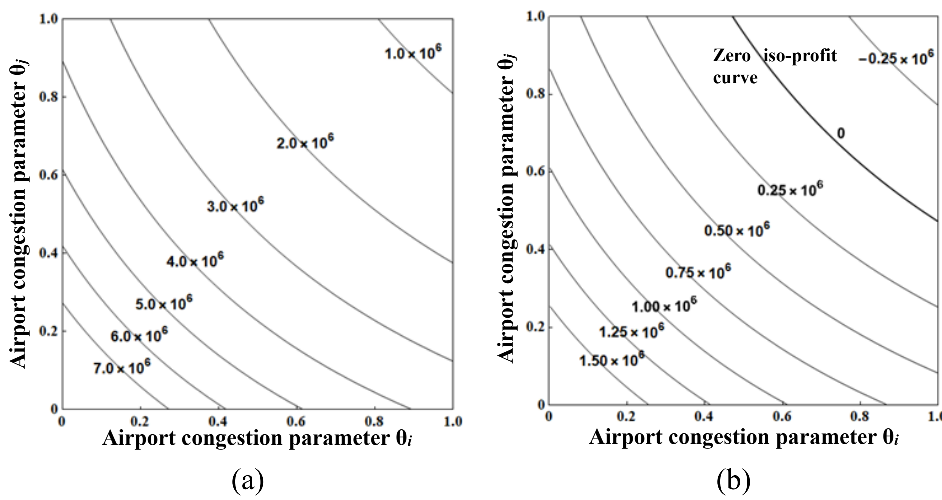


Fig. 15. Effects of θ_i and θ_j on total airport profit with one or two cooperating airlines: (a) airport non-collaboration; (b) airport collaboration.

Fig. 15 indicates the effects of the airport congestion parameters θ_i and θ_j on the difference of the total airport profits under the HSR cooperation with only one airline and with each of two airlines when the substitution parameter is fixed as λ = 0.3. It can be seen in Fig. 15a that without airport cooperation, the air-HSR cooperation with two airlines is better than that with only one airline in the whole plane of (θ_i, θ_j). This is because the difference of the total airport profits $\tilde{\Phi}_{III}^{(*)} - \Phi_{III}^{(*)}$ would be positive. However, with airport collaboration, as is shown in Fig. 15b, the zero iso-profit curve (i.e., $\tilde{\Phi}_{IV}^{(*)} - \Phi_{IV}^{(*)} = 0$) divides the whole plane into two parts: a positive region (lower-left corner) and a negative region (upper-right corner). This means that when the hub airport congestion cost is relatively large, a scheme of the HSR cooperation with fewer cooperating airlines is a better choice for the MAS.

7. Conclusion and further studies

This paper investigates the effects of the air-HSR cooperation, inter-airport relationship, and airport ownership issues in a multi-airport region. Airport ownership effect is analyzed through the analysis of two benchmark cases, namely the profit-maximizing private regime vs. the welfare-maximizing public regime. We model and compare market equilibria across six scenarios classified according to inter-airport relationship, airport objectives, and relationships between the airline and HSR that provide air-HSR service. We also extend the proposed models to consider airline heterogeneity and air-HSR revenue-sharing issues.

Our analysis leads to some important and insightful findings. First, an airline is more likely to provide air-HSR service when there is significant cost associated with congestion, low degree of substitution between direct air service and air-HSR inter-modal service, or when the competition on the direct air route is not very significant. Many studies found that dominant airlines can achieve substantial competitive advantage at their hub airports. Capacity constraints and/or slot control at hub airport make it difficult for entrant airline to initiate new services, or incumbent competitors to increase their capacity, which help hub carrier to maintain its dominance. Our analysis however suggests that these conditions would favor an airline to offer the air-HSR service as a substitute. Therefore, government officials should seriously consider promoting such inter-modal services which would contribute to both competition and congestion issues at hub airports. Second, under the private airport regulatory regime, (i) the effect of airport collaboration on the profit of transfer airport is ambiguous, regardless of air-HSR cooperation or not; (ii) although the air-HSR cooperation can enhance total profit of the airport system under the airport collaboration, its effect is undetermined when airports make separate decisions; and (iii) although the full cooperation can lead to the highest total profit of the airport system, it may not be the best scheme in terms of total social welfare. Third, the charges set by profit-maximizing airports are always positive, while the charges set by welfare-maximizing airports can be either positive or negative (i.e., subsidy to airlines). These findings suggest that regulators should be careful in ruling against subsidy to air-HSR service, which could benefit passengers using the air-HSR service (in terms of lower cost), as well as passengers continuing to use the direct air service (in terms of reduced congestion and lower cost). Fourth, air-HSR cooperation facilitates the shift of flights and passenger volume from hub airport to transfer airport, regardless of airports' objectives or ownership forms. Particularly, with profit-maximizing airports, the effect of air-HSR cooperation on the reduction of passenger volume at hub airport is more significant when airports collaborate. Airport collaboration helps congestion reduction at hub airports, whereas the market structure of independent airports helps the growth of air-HSR service. However, a full cooperation (i.e., air-HSR cooperation and airport collaboration) does not always lead to maximum social welfare. This highlights the importance for airports to think beyond congestion. For instance, competition between airlines, competition between airlines and air-HSR mode, and airport competition all should be taken seriously into account. Finally, an extension to incorporating the airline heterogeneity and air-HSR revenue sharing shows that under airport non-collaboration, the profit-maximizing airports prefer for the HSR cooperation with each of airlines on the air-HSR routes. However, under airport collaboration, the profit-maximizing airports prefer for the HSR cooperation with only one airline. Regardless of airport collaboration or not, the HSR firm would more like to cooperate with only one airline in terms of its profit, and the revenue-sharing ratio of each airline (or HSR) under the HSR cooperation with each of airlines increases (or decreases), compared to the HSR cooperation with only one airline.

In order to derive analytical solutions in a realistic setting, our models considered multiple factors across different market structures and scenarios. This comes with the cost of some strong assumptions, which should be relaxed in further studies. First, the MAS network structures used in this paper are simplified. Such a simplification allows one to derive analytical solutions that can explicitly reveal the relationships among variables of the models. However, it sacrifices the realism of model. In order to make the model more realistic, this paper can be further extended to consider a large-scale realistic network (see e.g., Hansen, 1990; Hsiao and Hansen, 2005) or a stylized general network (see for example Hendricks et al. 1997, 1999). Such a future study may obtain more realistic implications with network effect. Second, we assume that the airline of the air-HSR mode is an entrant but not one of the incumbent airlines providing direct flight services. In reality, the airline providing the air-HSR services can also be an incumbent airline providing direct flight services. In the Chinese aviation market, for example, China Eastern provides direct aviation service between Shenzhen and Shanghai and meanwhile air-HSR service on the Shenzhen-Nanjing-Shanghai route (i.e., Shenzhen-Nanjing by air and Nanjing-Shanghai by HSR). Such a strategy may be partly due to the domestic slot shortage at the Shanghai Hongqiao airport, and the incentive to combine traffic volume on the relatively thin routes between Shenzhen-Nanjing. Additionally, airline alliances and code-sharing can also be incorporated in the study of air-HSR cooperation. Third, it was assumed in this paper that the air/train service schedules are known for passengers, and the waiting time costs or the schedule delay costs at rail stations or airports were ignored. However, in reality the flight delays or HSR delays may happen due to various factors (e.g., bad weather), and passengers need to wait longer or change to other flights or trains (Kraus and Yoshida, 2002). Thereby, it will be more meaningful to develop a model to incorporate the effects of passenger wait time costs or the schedule delay costs. Fourth, it is assumed that the passengers are homogenous in this paper. In reality, however, passengers can be classified by their income and trip purposes (e.g., business or leisure). The high-income group or the business passengers may prefer for the non-stop flights while the low-income group or the leisure passengers are more likely to take the air-HSR integration services (Li and Sheng, 2016). It would thus be meaningful to extend the models to consider the passenger heterogeneity in terms of price discrimination (see for example Czerny and Zhang, 2011, 2014, 2015). Finally, a linear demand function was adopted to model passengers' choice behavior. Although such kind of function can be an approximation of more flexible demand functions through the first-order Taylor expansion and has been widely used in previous studies, more complicated demand functions and passenger choice model will be helpful for obtaining more practical conclusions, which can be implemented in a further study. Since the current model is already mathematically quite complex, some major improvements are needed in future studies. We hope the current study can provide an important avenue for investigating the related topics.

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Appendix A.

After introducing the direct HSR service between the OD market concerned, we can optimize the airport charges under the private regime by maximizing the airport profit. The resultant optimal airport charges for Scenarios I to IV are as follows.

$$\begin{cases} w_I^{h(*)} = \dfrac{2\left(2(5b^2-\lambda^2)(2bD-N\lambda^2)-(2b-\lambda)^2 N\lambda^2\right)\beta^a - \lambda(2b-\lambda)(2bD-N\lambda^2)\left(2(\beta^c-c^R)-\beta^R\right) - 2\lambda\left((5b-2\lambda)(2bD-N\lambda^2)+\lambda(2b-\lambda)(D-N\lambda)\right)\beta^{DR}}{2\left(4(5b^2-\lambda^2)(2bD-N\lambda^2)-(2b-\lambda)^2 N\lambda^2\right)}, \\ w_I^{t(*)} = \dfrac{-2n\lambda(2b-\lambda)(5b^2-\lambda^2)\beta^a + \left(2(5b^2-\lambda^2)(2bD-N\lambda^2)-N\lambda^2(2b-\lambda)^2\right)\left(2(\beta^c-c^R)-\beta^R\right) - \lambda\left(4(5b^2-\lambda^2)(D-N\lambda)+N\lambda(2b-\lambda)(5b-2\lambda)\right)\beta^{DR}}{2\left(4(5b^2-\lambda^2)(2bD-N\lambda^2)-(2b-\lambda)^2 N\lambda^2\right)}, \\ w_{II}^{h(*)} = \dfrac{\beta^a}{2} - \dfrac{\lambda\beta^{DR}}{4b}, \\ w_{II}^{t(*)} = \dfrac{2(\beta^c-c^R)-\beta^R}{4} - \dfrac{\lambda\left(2(5b^2-\lambda^2)(D-N\lambda)+N\lambda(2b-\lambda)(5b-2\lambda)\right)\beta^{DR}}{4\left((5b^2-\lambda^2)(2bD-N\lambda^2)-(2b-\lambda)^2 N\lambda^2\right)}. \end{cases} \tag{A1}$$

$$\begin{cases} w_{III}^{h(*)} = \dfrac{\left(2(2b+\lambda)(2bD-N\lambda^2)-N\lambda^2(2b-\lambda)\right)\beta^a - \lambda(2bD-N\lambda^2)(\beta^c-c^R) - \lambda\left(2(2bD-N\lambda^2)+\lambda(D-N\lambda)\right)\beta^{DR}}{4(2b+\lambda)(2bD-N\lambda^2)-N\lambda^2(2b-\lambda)}, \\ w_{III}^{t(*)} = \dfrac{-N\lambda(4b^2-\lambda^2)\beta^a + \left(2(2b+\lambda)(2bD-N\lambda^2)-N\lambda^2(2b-\lambda)\right)(\beta^c-c^R) - \lambda\left(2(2b+\lambda)(D-N\lambda)+N\lambda(2b-\lambda)\right)\beta^{DR}}{4(2b+\lambda)(2bD-N\lambda^2)-N\lambda^2(2b-\lambda)}, \\ w_{IV}^{h(*)} = \dfrac{\beta^a}{2} - \dfrac{\lambda\beta^{DR}}{4b}, \\ w_{IV}^{t(*)} = \dfrac{\beta^c-c^R}{2} - \dfrac{\lambda\left((2b+\lambda)(D-N\lambda)+N\lambda(2b-\lambda)\right)\beta^{DR}}{2\left((2b+\lambda)(2bD-N\lambda^2)-N\lambda^2(2b-\lambda)\right)}. \end{cases} \tag{A2}$$

Similarly, the optimal airport charges for Scenarios V and VI under the public regime are given as follows.

$$
\left\{
\begin{aligned}
w_V^{h(*)} &= \frac{\begin{vmatrix} \left(4(5b^2-\lambda^2)E-5bN\lambda(2b-\lambda)\right)\beta^a+\left(5b(2bD-N\lambda^2)-4\lambda(2b-\lambda)E\right)(\beta^c-c^R)-\lambda\left(5b(D-N\lambda)+2(5b-2\lambda)E\right)\beta^{DR}+\lambda\left(2(2b-\lambda)E-2N\lambda(b-\lambda)-\lambda D)\right)\beta^R & 2D(3\lambda^2-5b^2)+N\lambda^2(13b-10\lambda) \\ b\left(4(5b^2-\lambda^2)E-N\lambda^2(5b-2\lambda)\right)\beta^a-2b\lambda\left(2(2b-\lambda)E+\lambda(D-N\lambda)\right)(\beta^c-c^R)+b\lambda\left((5bD-2N\lambda^2)-2(5b-2\lambda)E\right)\beta^{DR}+b\lambda\left(2(2b-\lambda)E+\lambda(D-N\lambda)\right)\beta^R & -2b\lambda\left(\lambda(D-N\lambda)+2(2b-\lambda)E\right) \end{vmatrix}}{\begin{vmatrix} -10bN\lambda(b-\lambda)-2N\lambda^3 & 2D(3\lambda^2-5b^2)+N\lambda^2(13b-10\lambda) \\ 4Nb(b+2\theta)(5b^2-\lambda^2)-bN\lambda^2(23b-10\lambda) & -2b\lambda\left(\lambda(D-N\lambda)+2(2b-\lambda)E\right) \end{vmatrix}}, \\
w_V^{t(*)} &= \frac{\begin{vmatrix} -10bN\lambda(b-\lambda)-2N\lambda^3 & \left(4(5b^2-\lambda^2)E-5bN\lambda(2b-\lambda)\right)\beta^a+\left(5b(2bD-N\lambda^2)-4\lambda(2b-\lambda)E\right)(\beta^c-c^R)-\lambda\left(5b(D-N\lambda)+2(5b-2\lambda)E\right)\beta^{DR}+\lambda\left(2(2b-\lambda)E-2N\lambda(b-\lambda)-\lambda D\right)\beta^R \\ 4Nb(b+2\theta)(5b^2-\lambda^2)-bN\lambda^2(23b-10\lambda) & b\left(4(5b^2-\lambda^2)E-N\lambda^2(5b-2\lambda)\right)\beta^a-2b\lambda\left(2(2b-\lambda)E+\lambda(D-N\lambda)\right)(\beta^c-c^R)+b\lambda\left((5bD-2N\lambda^2)-2(5b-2\lambda)E\right)\beta^R+b\lambda\left(2(2b-\lambda)E+\lambda(D-N\lambda)\right)\beta^R \end{vmatrix}}{\begin{vmatrix} -10bN\lambda(b-\lambda)-2n\lambda^3 & 2D(3\lambda^2-5b^2)+N\lambda^2(13b-10\lambda) \\ 4Nb(b+2\theta)(5b^2-\lambda^2)-bN\lambda^2(23b-10\lambda) & -2b\lambda\left(\lambda(D-N\lambda)+2(2b-\lambda)E\right) \end{vmatrix}}, \\
w_{VI}^{h(*)} &= \frac{\begin{vmatrix} (2b-\lambda)\left(D(b+\lambda)+b(D-2bN)-2N\theta(2b+\lambda)\right)\beta^a+\left(2N\lambda\theta(2b-\lambda)-2b^2(D-N\lambda)-\lambda D(2b-\lambda)\right)(\beta^c-c^R)-\lambda\left((b-\lambda)(D-2bN)-2N\theta(2b-\lambda)\right)\beta^{DR} & 2(b-\lambda)(bD-N\lambda^2+bN\lambda)+2N\lambda\theta(2b-\lambda \\ N\lambda(2b-\lambda)^2\beta^a-\left(2b(2bD-N\lambda^2)+\lambda^2(D-N\lambda)\right)(\beta^c-c^R)+\lambda\left((2b-\lambda)D+(D-N\lambda)(2b+\lambda)\right)\beta^{DR} & 2b(2bD-N\lambda^2)-3\lambda^2(D-N\lambda)-2N\lambda^2(2b-\lambda) \end{vmatrix}}{2N(2b-\lambda)\begin{vmatrix} -b^2+\lambda^2-(2b+\lambda)\theta & (b-\lambda)(bD-N\lambda^2+bN\lambda)+N\lambda\theta(2b-\lambda) \\ \lambda(2b-\lambda) & 2b(2bD-N\lambda^2)-3\lambda^2(D-N\lambda)-2N\lambda^2(2b-\lambda) \end{vmatrix}}, \\
w_{VI}^{t(*)} &= \frac{\begin{vmatrix} -2N(2b-\lambda)(b^2-\lambda^2+\theta(2b+\lambda)) & (2b-\lambda)\left(D(b+\lambda)+b(D-2bN)-2N\theta(2b+\lambda)\right)\beta^a+\left(2N\lambda\theta(2b-\lambda)-2b^2(D-N\lambda)-\lambda D(2b-\lambda)\right)(\beta^c-c^R)-\lambda\left((b-\lambda)(D-2bN)-2N\theta(2b-\lambda)\right)\beta^{DR} \\ N\lambda(2b-\lambda)^2 & N\lambda(2b-\lambda)^2\beta^a-\left(2b(2bD-N\lambda^2)+\lambda^2(D-N\lambda)\right)(\beta^c-c^R)+\lambda\left((2b-\lambda)D+(D-N\lambda)(2b+\lambda)\right)\beta^{DR} \end{vmatrix}}{2N(2b-\lambda)\begin{vmatrix} -b^2+\lambda^2-(2b+\lambda)\theta & (b-\lambda)(bD-N\lambda^2+bN\lambda)+N\lambda\theta(2b-\lambda) \\ \lambda(2b-\lambda) & 2b(2bD-N\lambda^2)-3\lambda^2(D-N\lambda)-2N\lambda^2(2b-\lambda) \end{vmatrix}},
\end{aligned}
\right.
\tag{A3}
$$

where $E=(N-1)\theta-b$.