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Effects of high-speed rail and airline cooperation under hub airport capacity constraint

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ABSTRACT

This paper analyzes the effects of cooperation between a hub-and-spoke airline and a high-speed rail (HSR) operator when the hub airport may be capacity-constrained. We find that such cooperation reduces traffic in markets where prior modal competition occurs, but may increase traffic in other markets of the network. The cooperation improves welfare, independent of whether or not the hub capacity is constrained, as long as the modal substitutability in the overlapping markets is low. However, if the modal substitutability is high, then hub capacity plays an important role in assessing the welfare impact: If the hub airports are significantly capacity-constrained, the cooperation improves welfare; otherwise, it is likely welfare reducing. Through simulations we further study the welfare effects of modal asymmetries in the demands and costs, heterogeneous passenger types, and economies of traffic density. Our analysis shows that the economies of traffic density alone cannot justify airline–HSR cooperation.

1. Introduction

Since the first modern high-speed rail (HSR) began operation between Tokyo and Osaka, Japan in 1964, a number of countries including the United Kingdom, France, Spain, Germany, Italy, Belgium, the Netherlands and South Korea have also successfully launched HSR lines. By 2012, China had the world's largest HSR network, amounting to 9300 km of HSR coverage, with speeds between 200 km and 350 km per hour. In the United States, President Barack Obama's (fiscal year) 2012 budget allocated \$8 billion for HSR development, representing the first installment of a six-year, \$53 billion plan.

As train speeds have increased over the years, HSR has been viewed as a *de facto* substitute and effective competitor of air transport, especially for routes with distances up to 1000 km (e.g., Janic, 1993; Rothengatter, 2011). However, as pointed out by Givoni and Banister (2006), the relationship between HSR and air transport is far more complicated than pure competition alone. In particular, HSR can complement air service by offering connections between airports and nearby cities, and the potential for airline–HSR cooperation exists due to the hub-and-spoke network adopted by most major airlines. Under hub-and-spoke operation, two flights ("legs") are offered to passengers as one journey from their origin airport to the destination airport through a hub airport. With HSR, however, both these two legs need not be air flights: on legs where HSR service is comparable with flights in terms of (total) journey time and cost, HSR service may also be used in combination with a flight as one journey, with one booking for the entire two-leg trip. Such airline–HSR cooperation may be viewed simply as a special type of "code sharing" – i.e. two airlines cooperate to offer a hub-and-spoke operation with each offering one leg of a flight (and a non-operating carrier is allowed to put its code on the operating airline's flight number) – which has been a common practice in the airline industry (e.g. Oum et al., 1996; Brueckner, 2001; Ito and Lee, 2007; Gayle, 2008).

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There are several such airline–HSR cooperations in Europe. The AIRail Service provided by Lufthansa and Deutsche Bahn has connected Frankfurt airport with Stuttgart since March 2001, and with Cologne since May 2003. Passengers purchase a single ticket for the entire trip, and the luggage coordination between the airline and the HSR enables the passengers to pick up their luggage at the final destination without worrying about the transfer problem. Onboard the train, Deutsche Bahn staff provides services comparable to the ones offered onboard European short-haul flights. In France, Air France and SNCF launched TGV AIR in 1994, under which the intermodal passenger transportation between Charles de Gaulle (CDG) and Lille is exclusively operated by TGV (all Air France flights are cancelled). The TGV journey has an associated flight number appearing in the airline's computer reservation system (CRS), but luggage check-in is not included in the intermodal service. Similarly, Thalys International has cooperated with several airlines (Air France, KLM, American Airlines, Lufthansa and SN Brussels) to provide intermodal services to passengers on three Thalys links, namely, Brussels-CDG, Anvers-Schiphol, and Paris (Nord)-Brussels National Airport. These agreements differ from TGV AIR in that travelers check in at the rail stations for the entire journey. In Switzerland, the Swiss railway operator, SBB, cooperates with Swiss Airlines and Finnair to offer an intermodal product, called FlugZug, which covers four destinations (Basel, Bern, Lausanne and Lucerne) beyond Zurich. This product is displayed on the airlines' CRSs such that it looks like a Swiss or Finnair "flight." The traveler is "through checked" and obtains a boarding pass for the train leg of the journey. The service originally offered luggage through-check but the luggage transfer was stopped eventually due to under-utilization (Cokasova, 2006).

While airline–HSR cooperation has become more popular, overall it is still a relatively new phenomenon and so its market outcomes and welfare effects are largely unknown to date. Such cooperation can obviously hurt competition between the two modes in the markets where prior competition between the two occurs. A less obvious question is how such cooperation affects other "secondary" markets, owing to the network nature of a transportation system. The European Union appears to encourage such cooperation, stating in its White Paper that "network planning should therefore seek to take advantage of the ability of HSR to replace air transport and encourage rail companies, airlines and airport managers not just to compete, but also to cooperate" (European Commission, 2001); no rigorous analysis was given however. In the existing literature the two main arguments in favor of airline–HSR cooperation are (1) the relief of congestion at some major airports subject to capacity constraints and (2) the reduction of environmental pollutions (Givoni and Banister, 2006; Socorro and Viecens, 2013), as HSR service can divert airport traffic and is further considered a cleaner mode of transportation than air service, on a per-passenger basis. The arguments are made largely qualitatively with the use of empirical observations.

The present paper investigates analytically air transport–HSR interactions so as to address the impact of airline–HSR cooperation on market outcome and social welfare. Our investigation incorporates some of the most salient features of the two modes: in addition to an explicit examination of potential hub airport capacity constraints, we consider modal asymmetries in the demands and costs, heterogeneous passenger types, and economies of traffic density. Such an exercise is important because airline–HSR cooperation can involve substantial investment in access/connecting facilities and management time and effort. A better understanding of its impact is necessary and timely given that China is developing HSR quite ambitiously and countries like Brazil, India, Russia, Turkey, the UK and the US are evaluating the options of investing in HSR (Fu et al., 2012).

We show that airline–HSR cooperation will, as expected, reduce traffic in the markets where prior competition between the partners occurs, but may increase traffic in other markets of the network. The cooperation would improve social welfare, independent of whether or not the hub capacity is constrained, as long as the substitutability between air service and HSR service in the overlapping markets is low. However, if the modal substitutability is high (and hence the negative effect from dampening competition becomes larger), then hub capacity plays an important role in assessing the welfare impact. If the hub airports are significantly capacity-constrained, then airline–HSR cooperation could help alleviate the constrained capacity and benefit passengers in the non-overlapping markets of the network, leading to a net welfare improvement. Otherwise, the cooperation should be carefully examined, owing to its likely welfare-reducing effect. Through simulations we further find that airline–HSR cooperation is welfare enhancing irrespective of the hub capacity level if any one of the following conditions holds: (1) the unit cost of the HSR operator is sufficiently lower than that of the airline; (2) the HSR service is sufficiently superior to that of the airline; (3) the price sensitivity of HSR demand is higher than that of airline demand; and (4) a sufficiently large proportion of the passengers are business passengers. Our analysis shows that the economies of traffic density alone cannot justify airline–HSR cooperation. Moreover, when the density effect in the air sector is strong, the cooperation is less likely to be welfare enhancing under hub capacity constraints; but when the density effect in the rail sector is strong, this cooperation is more likely to improve welfare.

The existing literature focuses mainly on the competition aspect of the airline–HSR interaction. For example, Gonzalez-Savignat (2004) indicates that HSR service significantly reduces the market share of air transport when the two modes compete head-on. Park and Ha (2006) find that the opening of the first HSR line in South Korea has a significant (negative) impact on the domestic air transport industry. Adler et al. (2010) use a game theory setting to analyze aviation–HSR competition in the medium- to long-distance transport markets. They conclude that the European Union should encourage the development of the HSR network across Europe. With a Hotelling (differentiated Bertrand) model in which the HSR's objective is to maximize a weighted sum of welfare and profit, Yang and Zhang (2012) show that both airfare and HSR fare fall as the weight on welfare rises, and that airfare decreases, and HSR fare increases, in the airport access time. Behrens and Pels (2012) use pooled cross-sectional data from the London-Paris passenger market to identify the degree to and conditions under which HSR is a viable substitute for airline travel. They show empirically that there is fierce competition between aviation and HSR,

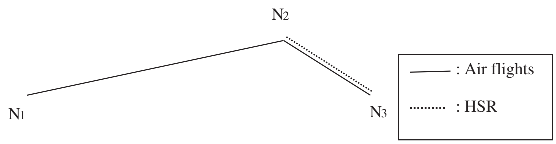

Fig. 1. Network structure.

and that the frequency of trips offered, total travel time and distance to the UK port are the main determinants of travelers' behavior in terms of their modal choice.

Research on airline–HSR cooperation is relatively rare in the literature, and is composed mostly of case studies and simulations.[1] Using the case of London's Heathrow airport, Givoni and Banister (2006) examine the possibility of airline–HSR intermodal integration and its potential benefits for airlines and the society. Cokasova (2006) undertakes a microscopic (operational) passenger and baggage movement simulation at an airline–HSR intermodal airport terminal to analyze the impact of intermodal passenger flow on such factors as passenger throughput and passenger delays. The simulation results show that intermodal passenger movement is socially beneficial only at airports with a large volume of short-haul frequent traffic, but the intermodal movement nonetheless increases the level of passenger delays. Socorro and Viecens's (2013) paper is the only attempt besides ours to investigate the impact of airline–HSR intermodal cooperation from an analytical point of view. They show that at capacity-constrained airports airline–HSR integration will reduce airport traffic and thereby relieve hub airport capacity (and reduce aircraft emissions), but the overall effect of the integration on welfare is ambiguous. While Socorro and Viecens's work is the most relevant to ours, they model hub airport capacity in a specific manner and make strong assumptions about the airlines' priorities for different markets. In particular, they assume that the airlines have a given order of importance for different markets, and fulfill all demands in one market before they consider the demands in another market. We adopt a different framework in which we are able to endogenize the airlines' decisions of allocating hub airport capacity to different markets, and hence avoid assuming that some markets are exogenously more important than others. In addition, we study the impact of some important features including economies of traffic density, vertical differentiation between modes, difference in price sensitivity of demand and heterogeneous passenger types, which were not addressed in Socorro and Viecens (2013). To the best of our knowledge, this paper is the first analytical work that uses an endogenous decision-making framework to study the effects of airline–HSR cooperation with a specific consideration of hub airport capacity and other salient features of the two transport modes.

The paper is organized as follows. Section 2 sets up the basic model and characterizes our analytical benchmark (the competition case). Section 3 examines the effects of airline–HSR cooperation on traffic and welfare, focusing on the role of hub airport capacity. Section 4 extends, using simulation analysis, the welfare analysis to situations with modal asymmetries in the demands and costs, heterogeneous passenger types, and economies of traffic density. Section 5 contains concluding remarks.

2. Model

2.1. Basic setting

Consider a network structure in which there are three cities with inter-city transport services being offered on only two links. The situation is depicted in Fig. 1, with three cities N_1, N_2 and N_3. One link, N_1N_2, is operated only by an air carrier; while the other, N_2N_3, is served by both the airline and an HSR operator. The different market structures on the two links may be due to geographical reasons. For instance, the first link is a long-haul journey and can be competitively served only by airlines, whilst the second link is short-haul with no distinct journey time difference between flights and HSR service.[2] It is also possible that cities N_1 and N_2 are separated by water or mountains, thus making HSR access technologically challenging. An example would be Morocco and Spain, which are not far away from each other in terms of distance but are separated by the Strait of Gibraltar, resulting in no train service between the two countries.[3] While relevant practically, this transportation network is also likely the simplest structure in which HSR–airline cooperation under hub airport capacity constraint can be

[1] This is in contrast to a large literature gauging the impacts of airline code sharing: International code-sharing alliances have been analyzed by, e.g., Oum et al. (1996), Brueckner and Whalen (2000), Brueckner (2001) and Whalen (2007). For analysis of US domestic airline alliances see, e.g., Clougherty (2000), Bamberger et al. (2004), Ito and Lee (2007), Gayle (2008) and Armantier and Richard (2008).

[2] Janic (1993) and Rothengatter (2011), among others, find that fierce competition between HSR and air transport can occur on links with distances up to 1000 km, most likely between 400 km and 800 km. HSR in general has little competitive impact on airlines for routes longer than 1200 km.

[3] In some cases, geographical obstacles may be overcome by technologies like the Channel Tunnel, but these cases are rare since the infrastructures are extremely expensive to build. Note that the different market structures on the two links might be due to political or technological factors also. For example, the air-only link connects two cities located in different countries, as international train service will likely impose a much higher level of cooperation between the two countries in laws, customs, and rail track compatibility.

addressed. It contains not only the market in which HSR and air transport directly compete prior to their cooperation but also other markets which, as we shall show, will be affected by such cooperation owing to strategic interactions in a transportation network.[4]

With three cities there are in total three origin–destination (OD) markets, which are N_1N_2, N_2N_3 and N_1N_3. As indicated above, the N_1N_2 market is served only by the airline (hereafter, the *HSR-inaccessible market*), whereas the N_2N_3 market is served by both the airline and the HSR (hereafter, the *HSR-accessible market*). In addition, the air carrier serves the N_1N_3 market using a hub-and-spoke strategy with N_2 as its hub. That is, it carries passengers from N_1 to N_3 (and back) through hub N_2 and so there is no direct flight service in the N_1N_3 market (hereafter, the *connecting market*). This structure is treated as exogenous for two reasons. First, major (legacy) carriers have adopted the hub-and-spoke strategy since the advent of deregulation (e.g., Zhang et al., 2011), which is long before HSR became a legitimate competitor to airlines. Competition from HSR, important and noteworthy as it is, does not appear to have forced airlines to change their networks from hub-and-spoke to "point-to-point".[5] Second, the factors considered in this paper, including hub airport capacity constraint and economies of traffic density, will only be significant under a hub-and-spoke network. This is because the economies of traffic density are a major reason why airlines adopt hub-and-spoke in the first place (e.g., Hendricks et al., 1995; Oum et al., 1995) and hub airports usually encounter capacity constraints owing to their "connecting" function (e.g., Ball et al., 2010).

Following Singh and Vives (1984) we use a quadratic consumer utility function:

$$U = \sum_i \sum_j \alpha_i^j q_i^j - \frac{1}{2} \sum_i \left(\sum_j \beta_i^j q_i^{j^2} + 2\gamma \prod_j q_i^j \right) \tag{1}$$

where $i = 1, 2, 3$ indicates the three OD markets (1 for N_1N_2, 2 for N_2N_3, and 3 for N_1N_3), whereas j indicates the transportation products. Specifically, only air service is available in the N_1N_2 market, so $j = A$ when $i = 1$ (A for air service). With both air flights and HSR service being provided in the N2N3 market, $j = A$ or R when $i = 2$ (R for HSR service). The connecting market (N_1N_3) requires special attention, since its market structure will be different under the two scenarios (competition and cooperation) investigated in this paper. We assume that when the airline and the HSR operator are pure competitors, a connecting flight is the only product available in this market; but if the airline cooperates with the HSR operator, passengers can choose connecting flight or flight–HSR connecting service to complete their journeys. In other words, $j = AA$ when $i = 3$ under airline–HSR competition (AA for connecting flight), but $j = AA$ or AR when $i = 3$ under airline–HSR cooperation (AR for flight–HSR connecting service). The assumption corresponds to the observation that cooperation between the two modes can significantly increase attractiveness of the flight–HSR connecting service by integrating tickets, coordinating schedules, providing connections between airports and train stations and possibly streamlining baggage transfer. As a consequence, passengers could treat it as a valid alternative to the connecting-flight service (Cokasova, 2006; Grimme, 2007).

Specification (1) implies that air service and HSR service are horizontally differentiated in the same market. This is justifiable by noting that for passengers the most important quality differentiator between the two modes is total journey time (e.g., Cokasova, 2006; Behrens and Pels, 2012). As analyzed in Yang and Zhang (2012), although air service results in a lower travel time for most routes, passengers in general need to spend more access/egress time for a flight, owing to its complicated check-in and security-check procedures as well as to the fact that airports are usually located far away from city centers. As a result, the total journey times of the two modes may vary across different passengers due to the access/egress times. Specifically, we consider that the two services are (imperfect) substitutes in the HSR-accessible market and the degree of substitutability is captured by parameter γ, with $\gamma \in [0, 1]$ and larger values of γ indicating more substitutable services.

For simplicity we first assume, in Sections 2 and 3, $\alpha_i^j = \alpha$ and $\beta_i^j = 1$ across all i's and j's. Note that α_i^j measures service quality in a vertical sense, so the case of the two modes being vertically differentiated is abstracted away from the analysis. (We will relax these assumptions and consider, in Section 4, the case in which α_i^j and β_i^j are heterogeneous across the modes.) In the analysis, the common parameter $\alpha$is used to represent the market size.[6] Following Yang and Zhang (2012), we further consider that the airline and the HSR operator choose quantities to maximize their profits. That is, the two modes engage in Cournot competition, taking airport and other capacities as given. This is, in a sense, a direct consequence of our intention for the model to be short run (in which case assuming Cournot competition would probably be more appropriate, because of capacity constraints) rather than long run (in which case Bertrand competition would probably be more appropriate).[7]

[4] This network structure is similar to the airline networks examined in, e.g., Brueckner and Spiller (1991) and Oum et al. (1995).

[5] To our knowledge, there is no reported case of airline de-hubbing as a result of HSR competition. Fu et al. (2012) state that an effective hub-and-spoke network is a way to confront HSR competition, suggesting that even if an airline network were influenced by HSR competition, it would be from a point-to-point network to a hub-and-spoke network, not the other way around.

[6] Another (and more accurate) interpretation of α is the "highest willingness-to-pay" of passengers in a particular market, given that it is the intercept of the inverse demand functions. The intercept of the demand functions is the real "market size". These two are identical for a monopoly market, but are slightly different for an oligopoly market. For a duopoly market, the real "market size" is $\alpha/(1 + \gamma)$, which is related not only to α but also to substitutability factor γ. Overall these two concepts are closely related and can be used interchangeably.

[7] There are some good reasons to believe that quantity competition might be more realistic than price competition in the present case. First, Quinet and Vickerman (2004, p. 263) note: "The general idea which emerges from the theoretical analysis is that when transport capacities are high, or can be enlarged through the transfer of capacity from other locations, and the services provided are not differentiated, then competition is likely to be of a Bertrand type, based on price. . . .If, on the other hand, capacity is difficult to increase, then competition is likely to be of a Cournot type, based on quantities. This is the case found, for example, in rail, maritime or inland waterway transport." The main reason why high-speed rail capacity is difficult to change (relative to the ease and rapidity with which prices can be adjusted) is that its investment is lumpy, time-consuming and irreversible. Second, Brander and Zhang (1990, 1993), for example, find some empirical evidence that rivalry between duopoly airlines is consistent with Cournot behavior. We discuss the issue further in the concluding remarks.

Another issue we need to address is the feasible range of parameter combinations. Here feasibility requires three groups of conditions: (1) the non-negativity conditions for (equilibrium) traffic volumes, prices, profits, marginal costs and marginal revenues; (2) the second-order conditions held for each maximization problem; and (3) the stability conditions of Cournot equilibrium. For the cases considered in Sections 2 and 3, feasibility does not impose any extra bounds for the parameters under consideration. However, it does play a role when other features (e.g., economies of traffic densities) are taken into account in Section 4.

2.2. Benchmark case: modal competition

With passengers' maximizing utility subject to budget constraint, it is straightforward to obtain the inverse demand functions for the three markets. Under the competition scenario, these functions are given by

$$p_1^A = \alpha - q_1^A \tag{2}$$

$$p_2^A = \alpha - q_2^A - \gamma q_2^R \tag{3}$$

$$p_2^R = \alpha - q_2^R - \gamma q_2^A \tag{4}$$

$$p_3^{AA} = \alpha - q_3^{AA} \tag{5}$$

Further, the airline's maximization problem is given as,

$$\begin{aligned} &\max_{\{q_1^A, q_2^A, q_3^{AA}\}} \pi^A = p_1^A q_1^A + p_2^A q_2^A + p_3^{AA} q_3^{AA} - C_1^A(q_1^A + q_3^{AA}) - C_2^A(q_2^A + q_3^{AA}) \\ &\text{s.t.} \quad q_1^A + q_2^A + 2q_3^{AA} \leqslant K \end{aligned} \tag{6}$$

where K denotes the hub airport capacity, which may be fully utilized; the superscripts of the cost functions (C_1^A and C_2^A) denote the operator (the same apply to the following expression for HSR) and the subscripts denote the links (1 for N_1N_2 and 2 for N_2N_3). Similarly, the problem of the HSR operator is given as,

$$\max_{q_2^R} \pi^R = p_2^R q_2^R - C_2^R(q_2^R) \tag{7}$$

Social welfare is given by the sum of consumer surplus and producer surplus. In this benchmark case it is equal to ("hat" denoting the values of variables in the competition case):

$$\widehat{W} = \widehat{CS} + \hat{\pi}^A + \hat{\pi}^R \tag{8}$$

The consumer surplus is given by

$$\widehat{CS} = \alpha(\hat{q}_1^A + \hat{q}_2^A + \hat{q}_2^R + \hat{q}_3^{AA}) - \frac{1}{2}(\hat{q}_1^{A^2} + \hat{q}_2^{A^2} + \hat{q}_2^{R^2} + \hat{q}_3^{AA^2} + 2\gamma \hat{q}_2^A \hat{q}_2^R) - (\hat{p}_1^A \hat{q}_1^A + \hat{p}_2^A \hat{q}_2^A + \hat{p}_2^R \hat{q}_2^R + \hat{p}_3^{AA} \hat{q}_3^{AA}) \tag{9}$$

For simplicity we first assume away cost asymmetry and the economies of traffic density: $C_i^A(Q) = c_A Q (i = 1, 2), C_2^R(Q) = c_R Q$ and $c_A = c_R = c_H$, which is, without loss of generality, further normalized to be c_H=0. A more complete analysis incorporating the modal cost asymmetry and economies of traffic density in both modes will be presented in Section 4.

The consideration of capacity in a multi-market network problem may cause diversity in market structure, owing to potential market abandoning. More specifically, when the hub capacity is very limited, it is possible for the airline to abandon one or more markets such that the resources are used to serve the most profitable markets. In our model, the connecting market would be the first market to be relinquished by the airline when the hub capacity constraint reaches a certain level, given that serving this market imposes the highest opportunity cost. Here it is reasonable to assume that such withdrawal does not affect the demand functions of the other two markets. The assumption is needed to guarantee consistent and tractable analytical results that cover the entire feasible range of hub airport capacity.[8]

It is also worth noting that whether the hub airport faces capacity constraint is determined not only by the capacity level but also by the market size. In effect, the Cournot equilibrium, characterized by the first-order conditions of problems (6) and (7), depends on the ratio of capacity over market size. We denote this ratio as k ($k = K/\alpha$) and present, in Table 1, the equilibrium traffic and welfare levels for different ranges of k under the competition scenario.[9]

Comparative statics analysis of the equilibrium traffic volumes in Table 1 gives rise to:

Proposition 1. *At the Cournot equilibrium (the competition scenario), (1) the number of passengers carried by the airline (non-strictly) increases with the hub capacity in all three markets, while the number of passengers carried by the HSR (non-strictly)*

[8] The cost structure is also assumed to be unaffected by the airline's withdrawal from any of the markets, which is reasonable since the fixed cost an airline needs to pay for a specific link is relatively small and so its decision of entering or exiting a market is fairly flexible even in the short run.

[9] A technical appendix with detailed derivation that gives rise to Table 1 (and the subsequent tables) is available upon request from the authors.

Table 1
Equilibrium traffic and welfare for ranges of k (ratio of hub capacity to market size): the competition scenario.

$k(=\frac{K}{\alpha})$	Traffic volume	Welfare
$k \leqslant \frac{\gamma}{4}$	$\hat{q}_1^A = \alpha k \quad \hat{q}_2^R = \frac{\alpha}{2}$	$\widehat{W} = \frac{\alpha^2}{8}(3 + 8k - 4k^2)$
$\frac{\gamma}{4} < k \leqslant \frac{8-4\gamma-\gamma^2}{4(4-\gamma^2)}$	$\hat{q}_1^A = \frac{\alpha[\gamma+k(4-\gamma^2)]}{8-\gamma^2}$ $\hat{q}_2^A = \frac{\alpha(4k-\gamma)}{8-\gamma^2}$ $\hat{q}_2^R = \frac{\alpha(4-2k\gamma)}{8-\gamma^2}$	$\widehat{W} = \frac{\alpha^2}{2(8-\gamma^2)^2}[2(24-\gamma^2) + 2k(64 - 24\gamma - 16\gamma^2 + \gamma^3 + \gamma^4) - k^2(32 - 20\gamma^2 + \gamma^4)]$
$\frac{8-4\gamma-\gamma^2}{4(4-\gamma^2)} < k \leqslant \frac{8+3\gamma}{2(2+\gamma)}$	$\hat{q}_1^A = \frac{\alpha[(4+\gamma-\gamma^2)+k(4-\gamma^2)]}{24-5\gamma^2}$ $\hat{q}_2^A = \frac{\alpha[(4-5\gamma)+4k]}{24-5\gamma^2}$ $\hat{q}_2^R = \frac{2\alpha[(6-\gamma)-k\gamma]}{24-5\gamma^2}$ $\hat{q}_3^{AA} = \frac{\alpha[4k(4-\gamma^2)-(8-4\gamma-\gamma^2)]}{48-10\gamma^2}$	$\widehat{W} = \frac{\alpha^2}{8(24-5\gamma^2)^2}[(2304 - 768\gamma - 280\gamma^2 + 80\gamma^3 + 15\gamma^4) + 8k(384 - 72\gamma - 144\gamma^2 + 5\gamma^3 + 15\gamma^4)$ $-4k^2(96 - 52\gamma^2 + 5\gamma^4)]$
$k > \frac{8+3\gamma}{2(2+\gamma)}$	$\hat{q}_1^A = \frac{\alpha}{2} \quad \hat{q}_2^A = \frac{\alpha}{2+\gamma}$ $\hat{q}_2^R = \frac{\alpha}{2+\gamma} \hat{q}_3^{AA} = \frac{\alpha}{2}$	$\widehat{W} = \frac{\alpha^2(24+16\gamma+3\gamma^2)}{4(2+\gamma)^2}$

decreases with the hub capacity. (2) If substitutability between air service and HSR service rises, then the number of passengers carried by the airline (non-strictly) increases in both the HSR-inaccessible market and the connecting market but (non-strictly) decreases in the HSR-accessible market, while the number of passengers carried by the HSR increases if the hub capacity is at a relatively low level, decreases if the hub capacity is at a relatively high level, and first falls and then rises for the middle capacity level.

Part 1 of the proposition is intuitive. Under the (binding) hub capacity constraint an increase in capacity K raises the airline's (equilibrium) outputs in all three markets, noting that at equilibrium the marginal profit from each additional unit of hub capacity is equalized across all the markets. The airline's commitment to greater output in the HSR-accessible market would induce an output contraction by the rival HSR, since the firms' outputs are strategic substitutes under the quantity competition with linear demands and costs. The second part of Proposition 1 is concerned with the comparative statics with respect to air–HSR substitutability. When the substitutability is higher, the rivalry in the HSR-accessible market is more intense, and the airline's profit margin in the market becomes lower as a result. The airline thus allocates more resources to the other two markets, increasing its outputs in these two markets and decreasing its output in the HSR-accessible market. The impact of a higher substitutability on the HSR operator is twofold: on the one hand, the more fierce the rivalry, the less output it would provide. On the other hand, due to the hub capacity constraint the airline is less aggressive in its rivalry with the HSR than it would have been without the constraint, which induces the HSR operator to act more aggressively. If the hub capacity is not too limited, the second effect is dominated by the first, leading to the HSR serving fewer passengers when the substitutability is higher. However, when the hub airport is seriously short of capacity, the second effect can become so strong that it dominates the first effect. In that case, the HSR's output is greater as the substitutability is higher.

3. Effects of airline–HSR cooperation

The competition case serves as a useful base for comparison with the case of airline–HSR cooperation. Here we consider full-scale cooperation between the airline and the HSR, under which the two firms make decisions jointly to maximize their total profit.[10] Under this cooperation scenario, the demand functions become:

$$p_1^A = \alpha - q_1^A \tag{10}$$

$$p_2^A = \alpha - q_2^A - \gamma q_2^R \tag{11}$$

$$p_2^R = \alpha - q_2^R - \gamma q_2^A \tag{12}$$

$$p_3^{AA} = \alpha - q_3^{AA} - \gamma q_3^{AR} \tag{13}$$

$$p_3^{AR} = \alpha - q_3^{AR} - \gamma q_3^{AA} \tag{14}$$

Note that Eqs. (10)–(12) are the same as Eqs. (2)–(4) as the cooperation will not alter the demand structures in the HSR-inaccessible market and the HSR-accessible market. The partners' problem is thus given by:

[10] Lower levels of cooperation also exist. As discussed in the introduction, airline-HSR cooperation exhibits various degrees of collaboration ranging from simple code sharing to joint schedule planning, single check-in and through baggage transfer. In these situations one firm could maximize its own profit and a fraction of its partner's profit (as in, e.g., Zhang and Zhang, 2006), and levels of cooperation could arise endogenously. The main insights obtained here can be extended to the partial cooperation cases as well.

Table 2
Equilibrium traffic and welfare for ranges of k (ratio of hub capacity to market size): The cooperation scenario.

$k(=\frac{K}{\alpha})$	Traffic volume	Welfare
$k \leqslant \gamma$	$\bar{q}_1^A = \frac{\alpha k}{2}$ $\bar{q}_2^R = \frac{\alpha}{2}$ $\bar{q}_3^{AR} = \frac{\alpha k}{2}$	$\overline{W} = \frac{\alpha^2}{8}(3 + 8k - 2k^2)$
$\gamma < k \leqslant \frac{3+\gamma}{2(2+\gamma-\gamma^2)}$	$\bar{q}_1^A = \frac{\alpha[\gamma+2k(1-\gamma^2)]}{6-4\gamma^2}$ $\bar{q}_2^A = \frac{\alpha(k-\gamma)}{3-2\gamma^2}$ $\bar{q}_2^R = \frac{\alpha(3-2k\gamma)}{6-4\gamma^2}$ $\bar{q}_3^{AR} = \frac{\alpha[\gamma+2k(1-\gamma^2)]}{6-4\gamma^2}$	$\overline{W} = \frac{\alpha^2}{8(3-2\gamma^2)}[9 + 8k(3 - \gamma - 2\gamma^2) - 4k^2(1 - \gamma^2)]$
$\frac{3+\gamma}{2(2+\gamma-\gamma^2)} < k \leqslant \frac{5+\gamma}{2(1+\gamma)}$	$\bar{q}_1^A = \frac{\alpha[1+k(1-\gamma^2)]}{7-4\gamma-\gamma^2}$ $\bar{q}_2^A = \frac{\alpha[(2-5\gamma-\gamma^2)+2k(1+\gamma)]}{2(1+\gamma)(7-4\gamma-\gamma^2)}$ $\bar{q}_2^R = \frac{\alpha[(7+\gamma)-2k(\gamma+\gamma^2)]}{2(1+\gamma)(7-4\gamma-\gamma^2)}$ $\bar{q}_3^{AA} = \frac{\alpha[2k(2+\gamma-\gamma^2)-(3+\gamma)]}{2(1+\gamma)(7-4\gamma-\gamma^2)}$ $\bar{q}_3^{AR} = \frac{\alpha[(2+5\gamma+\gamma^2)+2k(1-\gamma-2\gamma^2)]}{2(1+\gamma)(7-4\gamma-\gamma^2)}$	$\overline{W} = \frac{\alpha^2}{4(1+\gamma)(7-4\gamma-\gamma^2)}[3(5 + \gamma) + 4k(5 + \gamma - 5\gamma^2 - \gamma^3) - 2k^2(1 + \gamma - \gamma^2 - \gamma^3)]$
$k > \frac{5+\gamma}{2(1+\gamma)}$	$\hat{q}_1^A = \frac{\alpha}{2}$ $\hat{q}_2^A = \frac{\alpha}{2+2\gamma}$ $\hat{q}_2^R = \frac{\alpha}{2+2\gamma}$ $\bar{q}_3^{AA} = \frac{\alpha}{2+2\gamma}$ $\bar{q}_3^{AR} = \frac{\alpha}{2+2\gamma}$	$\overline{W} = \frac{3\alpha^2(5+\gamma)}{8(1+\gamma)}$

$$\begin{aligned} &\max_{\{q_1^A, q_2^A, q_3^{AA}, q_2^R, q_3^{AR}\}} \pi^{AR} = p_1^A q_1^A + p_2^A q_2^A + p_2^R q_2^R + p_3^{AA} q_3^{AA} + p_3^{AR} q_3^{AR} - C_1^A(q_1^A + q_3^{AA} + q_3^{AR}) - C_2^A(q_2^A + q_3^{AA}) - C_2^R(q_2^R + q_3^{AR}) \\ &\text{s.t.} \quad q_1^A + q_2^A + q_3^{AR} + 2q_3^{AA} \leqslant K \end{aligned} \tag{15}$$

It is assumed, again (in this section), that $C_i^A(Q) = c_A Q\ (i = 1, 2), C_2^R(Q) = c_R Q$, $c_A = c_R = c_H$ and $c_H = 0$.[11] Consumer surplus and social welfare are, respectively, expressed as ("bar" denoting the values of variables in the cooperation case):

$$\begin{aligned} \overline{CS} = &\alpha(\bar{q}_1^A + \bar{q}_2^A + \bar{q}_2^R + \bar{q}_3^{AA} + \bar{q}_3^{AR}) - \frac{1}{2}(\bar{q}_1^{A^2} + \bar{q}_2^{A^2} + \bar{q}_2^{R^2} + \bar{q}_3^{AA^2} + \bar{q}_3^{AR^2} + 2\gamma\bar{q}_2^A\bar{q}_2^R + 2\gamma\bar{q}_3^{AA}\bar{q}_3^{AR}) \\ &- (\bar{p}_1^A\bar{q}_1^A + \bar{p}_2^A\bar{q}_2^A + \bar{p}_2^R\bar{q}_2^R + \bar{p}_3^{AA}\bar{q}_3^{AA} + \bar{p}_3^{AR}\bar{q}_3^{AR}) \end{aligned} \tag{16}$$

$$\overline{W} = \overline{CS} + \bar{\pi}^{AR} \tag{17}$$

The (equilibrium) traffic and welfare levels in the cooperation case are summarized in Table 2. It can be easily seen from the table that Proposition 1 holds largely for the cooperation case as well. The only difference is in the connecting market, due to the introduction of the flight–HSR connecting service. When γ is small, the number of passengers taking the joint flight–HSR service increases with the hub capacity level; but when γ is sufficiently large, this number first rises and then falls. The flight–HSR connecting service is special because its provision requires the services of both the airline and the HSR operator. On one hand, the larger the hub capacity, the larger the number of passengers the airline can serve, raising the flight–HSR connecting traffic. On the other hand, an increase in the hub capacity will increase the number of connecting flight passengers, which in turn will reduce the amount of flight–HSR connecting traffic through a substitutability effect. When γ is large, the substitutability effect dominates the pure capacity effect, so the flight–HSR connecting traffic falls. For this reason, the fall will only happen when the hub capacity is large enough to support both the connecting flights and the flight–HSR connecting service.

It should be noted that although Tables 1 and 2 cover all possible values of the airport capacity/market size ratio, it does not necessarily mean that these ranges are equally important. For instance, the situations when the hub airport is extremely capacity-constrained, which correspond to the first few rows in both tables, may not be very common in reality. Even if new terminals or new airports cannot be built due to certain reasons, alternative infrastructure solutions would be proposed and passenger behavior is also likely to adapt accordingly even in the short run. Therefore, it may be worthwhile to pay more attention to the bottom parts of the two tables. Bearing this in mind can be helpful for the interpretation of the tables.

With Tables 1 and 2, we are able to compare the two scenarios and draw conclusions about the impact of the airline–HSR cooperation on traffic volumes and welfare. The details are presented in Tables A1 and A2 (see Appendix A). The comparison first reveals underlying reasons for the diversified market forms observed in real-world airline–HSR cooperation projects.[12] In particular, the market form/product choice following airline–HSR cooperation could depend on the hub capacity level also (rather than just on the degree of cooperation). We summarize the effects of the airline–HSR cooperation in two propositions, one for traffic volumes (Proposition 2) and the other for welfare levels (Proposition 3):

Proposition 2. *The airline–HSR cooperation will (non-strictly) reduce traffic in the HSR-accessible market and strictly increase traffic in the connecting market. Furthermore, it can increase or decrease traffic in the HSR-inaccessible market.*

[11] It can be easily seen that the total profit under cooperation will not be lower than that under competition, and so the airline and the HSR have incentives to cooperate.

[12] For example, ever since Air France and SNCF cooperated, all Air France flights between Lille to Charles de Gaulle have been cancelled, with only TGV train service being available on the route. However, passengers travelling between Frankfort and Stuttgart can choose a Lufthansa flight or a Deutsche Bahn train to complete their trips, despite the fact that these two companies have formed a close cooperative relationship in this market. In fact, both services can be purchased from the Lufthansa website.

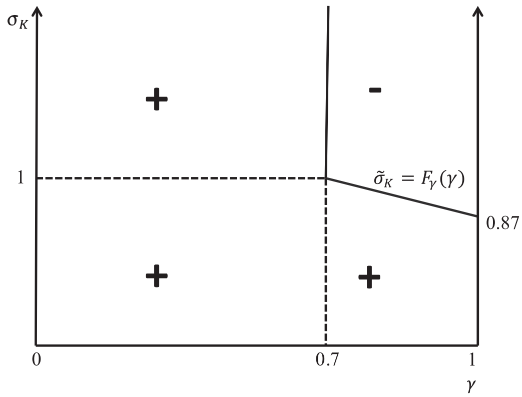

Fig. 2. Welfare effects of airline–HSR cooperation: The γ–σ_K interaction. *Note:* In this figure (and in Figs. 3 and 5–7), the regions with the + (−) sign are the regions where the airline–HSR cooperation increases (decreases) welfare.

It is noted that the effect of the airline–HSR cooperation on traffic in the HSR-inaccessible market depends on the value of substitutability parameter γ. For example, if γ is sufficiently large, q_1^A in the third row of Table A1 always rises following the cooperation, and q_1^A in the fourth row of Table A1 rises for large k but falls for small k. But for small γ, q_1^A in the third row increases when k is large and decreases when k is small, whilst q_1^A in the fourth row always decreases. This reflects the impact of cooperation on resource reallocation. When air and HSR services are close substitutes, the cooperation will significantly reduce the airline's output in the HSR-accessible market, freeing up a large amount of hub capacity, which can be used in the HSR-inaccessible market. Thus traffic in the HSR-inaccessible market tends to rise for a large range of hub capacity levels when substitutability between the two modes is high. For the other two markets however, the results are clear-cut. In the HSR-accessible market, traffic will fall because of the dampening of competition following the airline–HSR cooperation. In the connecting market, traffic always rises due to two reasons: first, the demand rises with the availability of the flight–HSR connecting service. Second, the hub capacity is reallocated from the HSR-accessible market to the connecting market, thus relieving its input constraint and increasing connecting traffic.

Proposition 3. *The airline–HSR cooperation improves welfare if either substitutability between air service and HSR service is sufficiently low, or the hub airport faces a severe capacity constraint. It reduces welfare, otherwise.*

Fig. 2 provides a graphical representation of Proposition 3. Instead of investigating the impact of the absolute level of hub capacity, K, on welfare, we introduce a measure of the relative hub capacity level as $\sigma_K = K/K_m$, where K_m denotes the minimum capacity level required for the hub airport to be not capacity-constrained.[13] Fig. 2 shows a threshold of substitutability parameter γ (i.e., the vertical demarcation line at $\gamma = 0.7$) that divides the welfare comparison into two parts. On its left side, the airline–HSR cooperation improves welfare regardless of hub capacity level σ_K. On the right side of the demarcation line, however, there exists a cutoff value of σ_K, above (below) which welfare falls (rises) following the airline–HSR cooperation. This cutoff value, $\tilde{\sigma}_K$, is between 0.87 and 1 and is a function of γ, i.e., $\tilde{\sigma}_K = F_\gamma(\gamma)$ with $\gamma \in [0.7, 1]$.[14] Thus, when the substitutability between air and HSR services is high ($\gamma > 0.7$) and there is no or little capacity constraint at the hub airport, the airline–HSR cooperation will reduce welfare.

Proposition 3 has clear policy implications. First, it shows that the modal substitutability in the market where the airline and the HSR would compete (absent an airline–HSR cooperation) plays a key role in assessing the welfare impact of such cooperation. As long as the modal substitutability is low, the cooperation would improve welfare, independent of whether or not the hub capacity is constrained. The social benefit comes from the fact that the flight–HSR connecting service – made possible by the cooperation – raises total demand in the connecting market, while the negative effect of dampening competition in the HSR-accessible market is relatively small (owing to the low substitutability). Second, when the modal substitutability is high and hence the negative effect from dampening competition becomes larger, it would benefit policy makers to pay attention to hub capacity. If the hub is significantly capacity-constrained, then the airline–HSR cooperation could help alleviate the constrained capacity and benefit passengers in other transport markets of the network, leading to a net welfare improvement.[15] Otherwise, the cooperation should be carefully examined, owing to its likely welfare-reducing effect.

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[13] Note that K_m depends on substitutability parameter γ and market-size parameter α, so a certain value of K might be either sufficient or insufficient under different combinations of γ and α. Since it is the airport capacity discrepancy (rather than the airport capacity itself) that drives the implications of the airline–HSR cooperation, α_K is a more appropriate index for discussing if the hub is capacity-constrained or not.

[14] $F_\gamma(\gamma)$ can be shown to be monotonically decreasing in γ, for $\gamma \in [0.7, 1]$.

[15] In particular, the cooperation enables the partners to redistribute traffic from the capacity-constrained air sector to the (unconstrained) rail sector, accommodating more passengers and thus improving economic efficiency. This "traffic reallocation" effect is increasing in the hub airport capacity shortage, so is decreasing in σ_K (and totally disappears when $\sigma_K \geqslant 1$). The larger the γ is, the larger the difference between the anticompetitive effect and the "demand stimulation" effect would be, and a greater hub capacity shortage is needed to make the net welfare effect positive. That is why in Fig. 2 $\tilde{\sigma}_K$ is decreasing in γ.

Furthermore, it would be interesting to see the impact of an airline–HSR cooperation on firms and passengers separately. This is because welfare is, as defined here, an equally weighted sum of producer surplus and consumer surplus. Under some circumstances however, policy makers may put different weights on these two types of surplus, and the policy implication of airline–HSR cooperation may be very different as a result.[16] Since the airline–HSR cooperation considered here will not reduce the joint profit but may under some conditions reduce welfare, the positive consumer-surplus effect of the cooperation is much less likely than the positive welfare effect. In particular, we find that the positive consumer-surplus effect arises only when the modal substitutability is very low and the hub airport is not capacity-constrained.[17] The passengers' gain comes mainly from the increased traffic in the connecting market due to the flight–HSR connecting service. When the hub capacity is ample and the modal substitutability is low, this gain is significant and it dominates the negative market-power effect naturally associated with the cooperation (which is small when the substitutability is low). This finding is crucial in policy making where consumer surplus is considered more important than producer surplus; it suggests that a stricter attitude may be adopted in the evaluation of such cooperation.

4. Extended analysis on welfare effects

4.1. Baseline for simulation study

In this section we relax our assumptions on cost and demand, in order to see the sensitivity of the welfare implications of the airline–HSR cooperation. For this purpose, we first construct a baseline case with values of α and γ estimated from relevant empirical studies, and then examine the impact of various factors one at a time.

The baseline case is derived from Behrens and Pels (2012), who conduct an interesting analysis of the airlines–HSR competition in the London–Paris passenger market. They report both the direct and cross elasticities of demand for the two transport modes, from which we could obtain a reasonable estimate of substitutability parameter . This is then followed by an estimation of market-size parameter α, leading to our baseline of $\alpha = 600$ and $\gamma = 0.71$.[18] Note that this γ value is fairly large, which, while fitting the London–Paris market well, may not be true for other markets.[19] For example, Fu et al. (2014) find that there exists substantial product differentiation between air travel and HSR service in Japan, suggesting a smaller value for γ. An examination of the relevant literature (e.g., Ivaldi and Vibes, 2008; Meunier and Quinet, 2012) suggests that while γ may cover a wide range of values due to the diversity of market characteristics, it is more likely to be relatively large.[20]

As shown in Fig. 2 of Section 3, there exists a threshold of substitutability parameter γ (0.7) that breaks the welfare comparison into two parts.[21] On one side of the threshold, the airline–HSR cooperation improves welfare irrespective of relative hub capacity level σ_K. On the other side, there exists a cutoff value of σ_K, denoted $\tilde{\sigma}_K$, such that welfare rises only when $\sigma_K < \tilde{\sigma}_K$. As shown below, similar patterns emerge for the variables investigated in this section, and these patterns will be illustrated using figures that are similar to Fig. 2.

4.2. Cost asymmetry (factor c)

Consider first that $c_R = 0$ and $c_A = c$ where the constant c can be non-zero. While the "common" view would be $c > 0$, it appears that the literature has yet to reach a consensus. Studies such as Froidh (2008) and Meunier and Quinet (2012) estimate that airlines have a higher unit operating cost than HSR operators. On the other hand, Levinson et al. (1997) report that HSR incurs a higher unit operating cost than airlines. Union Internationales des Chemins de Fer (UIC, 2008) suggests that low rail access charges need to be assumed for HSR to obtain a lower unit operating cost than airlines. For completeness, we do not impose restrictions on the sign of c. Nonetheless, if c is too large or too small, cases do exist in which one mode squeezes the other out of the market due to cost advantage. These cases are less relevant to our study and so are deliberately assumed away. As a consequence, the non-negativity condition in the feasibility analysis is more stringent than the other two groups of feasibility conditions.[22] In particular, feasibility requires $c \in (-246, 135)$.

Similar to Section 3, the welfare implication of the airline–HSR cooperation for the values of c and σ_K is illustrated in Fig. 3. There is a vertical demarcation line ($c = 6.55$in this case) that divides the welfare implication into two parts. When $c > 6.55$, welfare always rises after the cooperation, irrespective of the relative hub capacity level. When $c < 6.55$ however, there exists a cutoff value of σ_K, over which welfare is reduced by the cooperation. This value is an increasing function of

[16] Some papers such as Yang and Zhang (2012) have examined the importance of these "weights" in their analysis of airline-HSR interactions.

[17] See the 5th columns of Tables A1 and A2 for detailed comparison results.

[18] For the detailed procedure of parameter estimation, see Appendix B.

[19] Behrens and Pels (2012) suggest that there was fierce competition between the airlines and the HSR in the London-Paris passenger market. The distance between the two cities is 457 km, which also falls into the "fierce competition" distance range defined by Janic (1993) and Rothengatter (2011).

[20] Ivaldi and Vibes (2008) study the Cologne–Berlin market (600 km long) and report both the own and cross price elasticities of demand for the rail and the air sectors. Their study would imply a relatively high modal substitutability in that market. Meunier and Quinet (2012) demonstrate the own and cross price elasticities of demand for the two modes based on simulations of a few European markets, which would also imply a relatively high modal substitutability.

[21] Note that the baseline value of γ is higher than the threshold, meaning that the welfare implication of the airline–HSR cooperation is not universal (depending on σ_K as well).

[22] We adopt the same treatment in the subsequent cases of this section. If similar patterns are found, we shall just present the feasible ranges without much discussion.

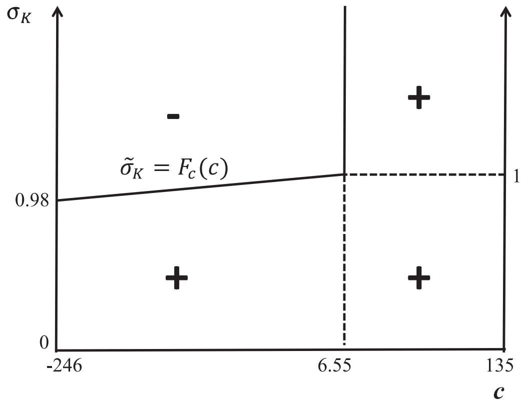

Fig. 3. Welfare effects of airline–HSR cooperation: The $c - \sigma_K$ interaction.

c, denoted $\tilde{\sigma}_K = F_c(c)$. That is, the larger (smaller) the HSR cost advantage (disadvantage), the more likely the cooperation is welfare improving. This finding is intuitive, because the demand-stimulation effect (a main positive impact of the airline–HSR cooperation) will be strengthened if HSR is more cost efficient than the airline. In particular, the smaller the HSR cost, the more the flight–HSR connecting traffic will be generated post-cooperation, and the greater the benefit of such cooperation. Therefore, the hub capacity shortage required to justify the cooperation decreases in c, and when c reaches a certain value, the airline–HSR cooperation becomes welfare enhancing unambiguously.

4.3. Economies of traffic density (factors θ_A and θ_R)

A prominent feature in the air and the rail sectors is the economies of traffic density: the unit cost on a link declines with total traffic on the link. The existence of the density effect in the airline industry has been demonstrated by a number of empirical studies (e.g., Caves et al., 1984; Brueckner et al., 1992; Brueckner and Spiller, 1994); strong economies of traffic density have also been identified in the rail industry (Braeutigam and Turnquist, 1984; McGeehan, 1993; Graham et al., 2003). To capture this feature we follow such papers as Brueckner and Spiller (1991), Zhang (1996), Brueckner (2001) and Bilotkach (2007) by using the following cost function for each link:

$$C^s(Q) = Q - \theta_s Q^2 \tag{18}$$

where Q is the total traffic of a specific mode on the link and θ_s is a positive density effect parameter, with $s = A, R$ representing the air and the rail modes, respectively.[23]

Given the baseline combination of α and γ, the feasible ranges for θ_A and θ_R are $[0, 0.0015)$ and $[0, 0.0028)$, respectively. We find that the thresholds over which the airline–HSR cooperation unambiguously improves welfare are not within the feasible combinations of θ_A and θ_R. This suggests that economies of traffic density alone cannot justify the intermodal cooperation. However, if the hub airport faces a certain level of capacity constraint, the cooperation can still be welfare enhancing. In other words, we can still find $\tilde{\sigma}_K$. Fig. 4 is an illustration of how $\tilde{\sigma}_K$ shifts with different combinations of θ_A and θ_R.

In Fig. 4, the contour lines represent different values of $\tilde{\sigma}_K$. We observe that given a specific θ_A, the larger the θ_R is, the larger the $\tilde{\sigma}_K$ will be. By contrast, given a specific θ_R, the larger the is, the smaller the $\tilde{\sigma}_K$ will be. This means that the economies of traffic density in the two transport modes play different roles in the evaluation of the airline–HSR cooperation. In particular, when the density effect in the air sector is strong, the intermodal cooperation is less likely to be socially beneficial under hub capacity constraints; but when the density effect in the rail sector is strong, this cooperation is more likely to improve welfare. The mechanism is similar to what we discussed in Section 4.2. Thus, the higher the cost advantage of the rail sector relative to the air sector (in terms of either the unit cost or the density effect), the more likely the cooperation is welfare enhancing.

4.4. Vertical differentiation (factor δ)

We have so far assumed that the two transportation modes are purely horizontally differentiated. As shown by Behrens and Pels (2012), vertical differentiation appears important between rail and air (in addition to the horizontal-differentiation aspect). This subsection considers a situation where the air–HSR differentiation is not only horizontal but also vertical. Recall that assuming vertical differentiation is equivalent to assigning various values to α_i^j in equation (1). Here we consider that

[23] Since link-specific total cost can be separated into variable costs and fixed costs, the economies can come from two sources: falling marginal costs and spreading fixed costs over more traffic. Specification (18) captures the case of falling marginal costs. Note that $\theta_s = 0$ represents the absence of density economies.

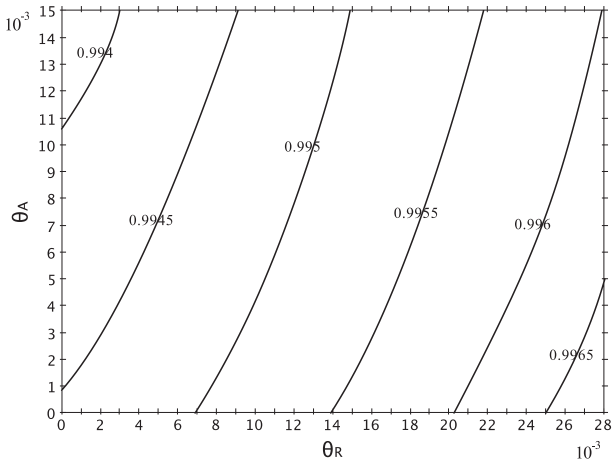

Fig. 4. Values of $\tilde{\sigma}_K$ for given θ_A and θ_R.

vertical differentiation exists only across the two modes but not across markets: $\alpha_1^A = \alpha_2^A = \alpha_3^{AA} = \alpha = 600$ whilst $\alpha_3^{AR} = \alpha_2^R = \delta\alpha = 600\delta$, with $\delta > 0$capturing vertical differentiation between the two modes. Which transport mode possesses a higher quality, i.e., whether or not, is generally case-dependent. As suggested by the empirical literature (e.g., Gonzalez-Savignat, 2004; Ivaldi and Vibes, 2008; Behrens and Pels, 2012; Fu et al., 2014), such factors as travel time and frequency play an important role in affecting passengers' perception about quality and hence their modal choice. And these factors may vary across different markets for both modes. Therefore, to make our analysis robust we allow to be greater or smaller than 1. In effect, the feasible range of δ is (0.71, 1.41).

We find that when δ is sufficiently large (>1.01) the airline–HSR cooperation always improves welfare. And when δ is relatively small, a cutoff value of σ_K can be found, above which the cooperation reduces welfare. This value $\tilde{\sigma}_K$ depends on δ, denoted $\tilde{\sigma}_K = F_\delta(\delta)$, and the corresponding welfare implication is illustrated in Fig. 5. As can be seen from the figure, $\tilde{\sigma}_K$ first decreases, and then increases, as δ rises. The analysis shows that the cooperation is more likely to be welfare improving when HSR is superior or much inferior to the airline with respect to quality. This is because two effects of the cooperation are related to the vertical differentiation between modes. First, the demand-stimulation effect increases monotonically with the relative attractiveness of the HSR, since the higher the quality of the HSR service is relative to the airline service, the more passengers will be attracted to the flight–HSR connecting service. Second, a new type of reallocation effect (other than the one concerning hub capacity discussed in Section 3) arises following the cooperation, since the cooperation allows more passengers to be redistributed from a low-quality product to a high-quality product. This effect increases with the quality differentiation between the two modes. When $\delta > 1$, these two effects both increase in δ, and they dominate the negative anticompetitive effect of the cooperation when $\delta > 1.01$. When $\delta < 1$, the demand-stimulation effect still increases but the reallocation effect decreases in δ. The net (positive) effect first decreases and then increases in δ, but is in general dominated by the negative anticompetitive effect.

4.5. Differential price sensitivities of demand (factor β)

Next we examine the impact of differential values of β_i^j which, for given α_i^j and γ, measure the price sensitivities of demand.[24] It is possible that β_i^j is different across the transport modes due to the heterogeneity of service characteristics. Empirical findings also support this possibility. For example, Ivaldi and Vibes (2008), Meunier and Quinet (2012) and Behrens and Pels (2012) find very different own price elasticities for airlines and HSR. Consider that $\beta_1^A = \beta_2^A = \beta_3^{AA} = 1$, while $\beta_3^{AR} = \beta_2^R = \beta$, with $\beta > 0$.[25] The feasibility analysis suggests that $\beta > 0.71$, which is reasonable given that $\gamma = 0.71$. We find that within the feasible β range, the airline–HSR cooperation unambiguously increases welfare when β is smaller than a particular value (0.97). For $\beta > 0.97$, the welfare implication of the cooperation can be ambiguous however, depending on both β and σ_K. Similar to Sections 4.2 and 4.4, the welfare implication for the case of differential price sensitivities of demand is summarized in Fig. 6.

From Fig. 6 we can see that $\tilde{\sigma}_K$ first decreases and then increases in β. Note that the larger the β, the smaller the price sensitivity of demand for HSR relative to the airline. This implies that it is more likely for the cooperation to be welfare enhancing when HSR demand is either very price sensitive or very price insensitive. The price sensitivity of demand would

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24 Assume that there are two products, *m* and *n*, in market *i*, the inverse demand function for product *m* is then given by $p_i^m = \alpha_i^m - \beta_i^m q_i^m - \gamma q_i^n$. The corresponding demand function is $q_i^m = [\beta_i^n(\alpha_i^m - p_i^m) - \gamma(\alpha_i^n - p_i^n)]/(\beta_i^m \beta_i^n - \gamma^2)$. The own price sensitivity of demand is thus $\beta_i^n/(\beta_i^m \beta_i^n - \gamma^2)$. Given a specific β_i^n and a specific γ, the larger the β_i^m, the smaller this sensitivity.

25 Ivaldi and Vibes (2008), Meunier and Quinet (2012) and Behrens and Pels (2012) all find that the own elasticity of demand is lower for HSR than for airlines, suggesting $\beta > 1$. To keep the analysis complete however, we also consider the case of $\beta < 1$.

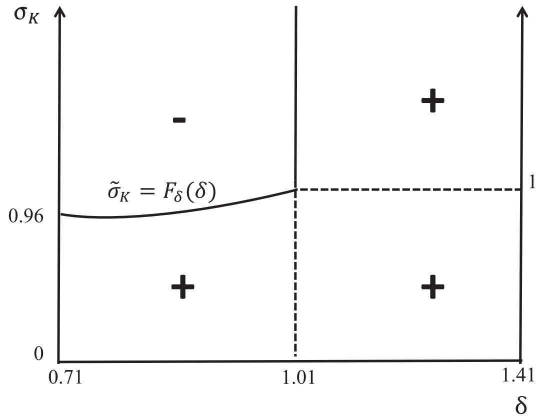

Fig. 5. Welfare effects of airline–HSR cooperation: The δ–σ_K interaction.

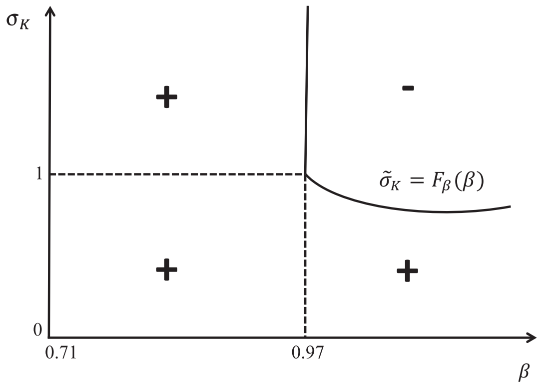

Fig. 6. Welfare effects of airline–HSR cooperation: The β–σ_K interaction. *Note:* β is not bounded on the right. $F_\beta(\beta)$ first decreases in β and then increases slowly but never reverts to 1 again.

have an impact on both the demand-stimulation effect and the anticompetitive effect. On one hand, the higher the price sensitivity of HSR demand, the lower the flight–HSR connecting service will be priced, and the more passengers will be served. In other words, the positive demand-stimulation effect monotonically decreases in β. On the other hand, when the price sensitivity of HSR demand is very high or very low, the anticompetitive effect of the cooperation is weak since the two modes do not compete fiercely in the first place. That is, the negative anticompetitive effect first increases and then decreases in β. When β is small, the (strong) demand-stimulation effect dominates the (weak) anticompetitive effect, thereby improving welfare unambiguously. As β increases, the anticompetitive effect first increases and dominates the ever decreasing demand-stimulation effect; and then the anticompetitive effect decreases, closing the gap between these two effects but never reversing the relationship again.

4.6. Heterogeneous passengers (factor φ)

Studies such as Gonzalez-Savignat (2004), Ivaldi and Vibes (2008), Czerny and Zhang (2011) and Behrens and Pels (2012) have stressed the distinction between different passenger groups, particularly between business and leisure passengers. It is suggested that these two groups exhibit large differences in both the willingness-to-pay and the degree of substitutability between transport modes (Ivaldi and Vibes, 2008). Therefore, where the aggregate demand is concerned, the percentage of these passenger groups may have an impact on both market size indicator α and modal substitutability parameter γ. In particular, the higher the percentage of business passengers in a market is, the larger the α and the smaller the γ.[26] Here we use parameter φ to denote the percentage of business passengers. Assuming that the interaction between this percentage and α as well as γ are both linear, we estimate, based on the information derived from Behrens and Pels (2012), that $\alpha = 494 + 298\varphi$ and $\gamma = 0.825 - 0.235\varphi$.[27] Further, it can be shown that the feasible range for φ is between 0 and 1.

[26] Ivaldi and Vibes (2008) explicitly state that the degree of substitutability between rail and air transport is higher in the leisure market than in the business market.

[27] Please refer to Appendix B for the detailed estimation procedure. Note that we adopt a very restricted functional form to describe the relationship between φ and α as well as γ, so as to give a rough idea about the role φ plays in the welfare implication of the airline-HSR cooperation.

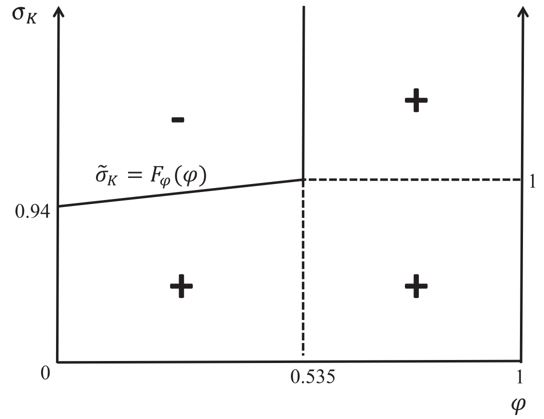

Fig. 7. Welfare effects of airline–HSR cooperation: The φ–σ_K interaction.

Table 3
Parameter estimates for the reference case.

α	600
δ	0.92
β	1.36
γ	0.71
c_A	126.4
c_R	63.8
θ_A	$9.7 * 10^{-5}$
θ_R	$1.6 * 10^{-4}$

It is straightforward to see that, when φ is larger than a specific value (0.535 in this case) the intermodal cooperation will improve welfare, irrespective of the hub capacity level. For $\varphi < 0.535$however, only when the hub airport is capacity-constrained can the cooperation be welfare improving. The situation is depicted in Fig. 7. The figure shows that $\tilde{\sigma}_K$ increases with φ (when $\varphi < 0.535$). Furthermore, the analysis reveals that the higher the percentage of business passengers in a market, the more likely the cooperation is welfare enhancing. This is because the higher the percentage of business passengers, the larger the market size and the smaller the modal substitutability. In other words, the (positive) demand-stimulation effect is larger while the (negative) anticompetitive effect is smaller, both pointing in the welfare-enhancing direction.

4.7. A reference case

In this subsection, we attempt to offer a complete picture of the welfare implications of airline–HSR cooperation. This is done with a reasonable case in which we incorporate all the factors that have been considered in the paper. More specifically, the utility function used to obtain the demand functions is given by:

$$U = \alpha(q_1^A + q_2^A + q_3^{AA}) + \alpha\delta(q_2^R + q_3^{AR}) - \frac{1}{2}[(q_1^{A^2} + q_2^{A^2} + q_3^{AA^2}) + \beta(q_2^{R^2} + q_3^{AR^2}) + 2\gamma(q_2^A q_2^R + q_3^{AA} q_3^{AR})] \quad (19)$$

whereas the cost functions for the two modes are:

$$C^A(Q) = c_A(1 - \theta_A Q)Q$$
$$C^R(Q) = c_R(1 - \theta_R Q)Q \quad (20)$$

Next, we need to derive a set of parameter estimates from relevant empirical studies. We first estimate α and γ as well as δ and β from Behrens and Pels (2012), and then obtain c_A and θ_A from Brueckner and Spiller (1994).[28] The estimation of c_R and θ_R, on the other hand, is based on information from Campos and de Rus (2009).[29] The estimates are listed in Table 3:

[28] Note that the data used in Brueckner and Spiller (1994) are from the fourth quarter of 1985, which is much earlier than the data sources of other empirical papers used for the estimation. It is reasonable to conjecture that c_A would be lower while θ_A would be higher if more recent data were available, due to the fact that technology developments tend to improve cost efficiency.

[29] The information in Levinson et al. (1997) also gives very similar estimates.

With this combination of parameters we find that when the hub airport does not face capacity constraint, welfare falls following the airline–HSR cooperation (226,687 vs. 236,672). Only when the hub capacity level is under a certain value (700), would the cooperation improve welfare. This reference case shows again the importance of hub capacity in assessing the welfare impact of airline–HSR cooperation.

5. Concluding remarks

This paper has developed a simple, tractable model to study the impact of cooperation between a hub-and-spoke airline and a high-speed rail (HSR) operator when the hub airport is under a possible capacity constraint. We found that the airline–HSR cooperation reduces traffic in the HSR-accessible market where prior competition between the partners occurs. But outside of this direct market, the cooperation increases traffic in the hub-and-spoke connecting market, and has an ambiguous effect on traffic in the HSR-inaccessible market. The airline–HSR cooperation improves welfare whenever the substitutability between air flights and HSR service is low – in this situation the anticompetitive effect of the intermodal cooperation is not strong and is likely to be dominated by its demand-stimulation effect in the connecting market. When the substitutability is high, then hub capacity plays an important role in assessing the welfare impact of airline–HSR cooperation. Such cooperation improves (reduces) welfare if the hub airport is (is not) seriously capacity-constrained.

We have further examined the impact of other factors on welfare through simulation. We found that the airline–HSR cooperation is welfare enhancing irrespective of the hub capacity level if any one of the following conditions holds: (1) the unit cost of the HSR operator is sufficiently lower than that of the airline; (2) the HSR service is sufficiently superior to the airline service; (3) the price sensitivity of HSR demand is higher than that of airline demand; and (4) a sufficiently large proportion of the passengers are business passengers. Our analysis shows that economies of traffic density alone cannot justify the airline–HSR cooperation. Furthermore, when the density effect in the air sector is strong, the cooperation is less likely to be welfare enhancing under hub capacity constraints. On the other hand, when the density effect in the rail sector is strong, this cooperation is more likely to be welfare enhancing. As airline–HSR cooperative activities have become more popular (but have yet to draw serious attention from researchers and regulators), these findings are suggestive to policy makers. A careful examination of airport capacity, network interactions and other salient features in both modes is warranted. In particular, some less-mentioned benefits of the cooperation, such as the market-expansion effect due to the creation of new intermodal service and the allocation-efficiency effect due to modal asymmetry in quality, should draw policy makers' attention.

The paper has also raised a number of issues and avenues for further research. First, we modeled airline–HSR rivalry as quantity competition, with the intention of examining a short-run model. In general, which model of competition is applicable to a particular market depends in large part on the production technology (in addition to the time horizon). In quantity competition firms commit to quantities, and prices then adjust to clear the market, implying the industry is flexible in price adjustments, even in the short run. On the other hand, in price (Bertrand) competition, capacity is unlimited or easily adjusted in the short run. Although there are some good reasons to believe that quantity competition may be more relevant for the present paper, it would be interesting to see how the results might change with price competition, and to further study the empirical relevance of alternative oligopoly models to the transport markets under consideration. Second, we considered the case of a single airline and a single HSR operator. In reality the markets are likely to have more firms, especially in the airline sector. When multiple firms in each sector converge in a network of transportation markets, the possibilities of strategic interactions will be enlarged and complicated. Extending the analysis to a framework with more competitors would be a useful future study.

Third, several empirical studies suggest that factors such as travel time and frequency can be important in airline–HSR interactions (Gonzalez-Savignat, 2004; Ivaldi and Vibes, 2008; Behrens and Pels, 2012; Fu et al., 2014). While the present paper has implicitly modeled (and, to a certain extent, studied) their impacts as the modal differentiation, horizontally and/or vertically, it would be a natural extension to explicitly incorporate these factors into a more complete analytical framework. Finally, we have abstracted away the environmental effects from our analysis. Whether HSR service is superior to air flights with respect to emissions remains controversial empirically (e.g., Chester and Horvath, 2010).[30] Even if environmental benefits do exist for HSR, some studies suggest that they are insignificant when deciding on the social desirability of HSR (de Rus, 2011). Furthermore, different countries may value environmental benefits differently, depending on their economic development stages and the focus of the government at the time.[31] However, the environmental impact needs to be taken into account for a more complete policy assessment on airline–HSR cooperation. A general conjecture may be that if HSR exhibits substantial advantage over air transport with respect to the environment, the intermodal cooperation tends to be more socially favorable.

[30] Although it is generally accepted that HSR incurs less per passenger-km emission than airlines, it also leads to additional environmental costs in terms of land occupied, barrier effects, visual intrusion and noise (de Rus, 2011). The environmental effect of the HSR technology is particularly acute in the construction phase. Kageson (2009) concludes "investment in high speed rail is under most circumstances likely to reduce greenhouse gases from traffic compared to a situation when the line was not built. The reduction, though, is small and it may take decades for it to compensate for the emissions caused by construction." This aspect is less relevant to our analysis since we study an existing HSR line, but it is still a notable point to consider in a more comprehensive investigation.

[31] In the present study we thus follow the advice of Sichelschmidt (1999) by focusing only on the "economic" issue. Nevertheless, as noted by an anonymous referee, there is little doubt that diverting air traffic to existing HSR lines is beneficial to the environment, and the environmental concern is a strong motive in individual circumstances for airline-HSR cooperation. See also Adler et al. (2010).

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Appendix A

We summarize, in Tables A1 and A2, the market structures before and after the airline–HSR cooperation, as well as the impact of the cooperation on traffic volumes, welfare and consumer surplus levels under different combinations of γ and k. Note that the cutoff value when comparing $(8-4\gamma-\gamma^2)/[4(4-\gamma^2)]$ and γ is not exactly $\sqrt{2}-1$, but it is very close. We neglect this small range for the sake of presentation clarity, but incorporating it will not alter our propositions.

Appendix B

B.1. Estimation of the utility function

Behrens and Pels (2012) use revealed preference data and estimate two logit models (the nested multinomial logit and the mixed multinomial logit) to examine the demand patterns of two types of passengers (leisure and business). They thus obtain four groups of estimation results. In addition, they look at six airport-airline pairs that give different estimates (Heathrow/Air France, Heathrow/British Airways, Heathrow/British Midland Airways, Gatwick/British Airways, Luton/easyJet, and City/Air France). We exclude the Luton/easyJet pair because easyJet, a low-cost carrier, does not adopt the hub-and-spoke network considered in our model. The City/Air France pair is excluded due to low traffic volume.

The cross elasticities of air demand with respect to the HSR fare are defined as $\varepsilon_{AR} = (\partial Q_A/\partial P_R)(P_R/Q_A)$, where A represents an airport/airline pair and R represents the HSR. They are equal to $P_R/(\gamma Q_A)$ in our model after adjustment with the own elasticities. The elasticities, the average fares and the traffic volumes are all reported in Behrens and Pels (2012), so γcan be easily estimated. We are able to obtain one $\gamma$for every airport/airline combination in every choice model. Subsequently we use the traffic volumes as a weight to obtain a weighted-average value for every model. The four weighted average γ's are 0.60 (nested-business), 0.81 (nested-leisure), 0.58 (mixed-business) and 0.84 (mixed-leisure). Taking weighted average again gives 0.71 as our final estimate.

Table A1
Effects of airline–HSR cooperation when $\gamma > \sqrt{2}-1$.

$k(=\frac{K}{\alpha})$	Pre-cooperation market equilibrium	Post-cooperation market equilibrium	Traffic-volume impact	Welfare and consumer-surplus impact
$k \leqslant \frac{\gamma}{4}$	Airline serves HSR-inaccessible market only	HSR-accessible market is served by HSR only, and only the flight–HSR connecting service exists in the connecting market	$\bar{q}_1^A < \hat{q}_1^A$ $\bar{q}_2^R = \hat{q}_2^R$ $\bar{q}_3^{AR} > 0$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\frac{\gamma}{4} < k \leqslant \frac{8-4\gamma-\gamma^2}{4(4-\gamma^2)}$	Airline serves both the HSR-inaccessible and HSR-accessible markets, but is not able to cover the connecting market	HSR-accessible market is served by HSR only, and only the flight–HSR connecting service exists in the connecting market	$\bar{q}_1^A < \hat{q}_1^A$ $\bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AR} > 0$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\frac{8-4\gamma-\gamma^2}{4(4-\gamma^2)} < k \leqslant \gamma$	Airline serves all three markets, but is still constrained by hub capacity	HSR-accessible market is served by HSR only, and only the flight–HSR connecting service exists in the connecting market	$\bar{q}_1^A \gtreqless \hat{q}_1^A$ $\bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AR} > \hat{q}_3^{AA}$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\gamma < k \leqslant \frac{3+\gamma}{2(2+\gamma-\gamma^2)}$	Airline serves all three markets, but is still constrained by hub capacity	Both the airline and HSR serve the HSR-accessible market, but only the flight–HSR connecting service exists in the connecting market	$\bar{q}_1^A \gtreqless \hat{q}_1^A$ $\bar{q}_2^A + \bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AR} > \hat{q}_3^{AA}$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\frac{3+\gamma}{2(2+\gamma-\gamma^2)} < k \leqslant \frac{5+\gamma}{2(1+\gamma)}$	Airline serves all three markets, but is still constrained by hub capacity	All available services are provided, but the hub airport is still under capacity constraint	$\bar{q}_1^A > \hat{q}_1^A$ $\bar{q}_2^A + \bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AA} + \bar{q}_3^{AR} > \hat{q}_3^{AA}$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\frac{5+\gamma}{2(1+\gamma)} < k \leqslant \frac{8+3\gamma}{2(2+\gamma)}$	Airline serves all three markets, but is still constrained by hub capacity	Airport does not face capacity constraint	$\bar{q}_1^A > \hat{q}_1^A$ $\bar{q}_2^A + \bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AA} + \bar{q}_3^{AR} > \hat{q}_3^{AA}$	$\overline{W} \gtreqless \widehat{W}$ $\overline{CS} < \widehat{CS}$
$k > \frac{8+3\gamma}{2(2+\gamma)}$	Airport does not face capacity constraint	Airport does not face capacity constraint	$\bar{q}_1^A = \hat{q}_1^A$ $\bar{q}_2^A + \bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AA} + \bar{q}_3^{AR} > \hat{q}_3^{AA}$	$\overline{W} \gtreqless \widehat{W}$ $\overline{CS} < \widehat{CS}$

Table A2
Effects of airline–HSR cooperation when $\gamma < \sqrt{2} - 1$.

$k(=\frac{K}{\alpha})$	Pre-cooperation market equilibrium	Post-cooperation market equilibrium	Traffic-volume impact	Welfare and consumer-surplus impact
$k \leqslant \frac{\gamma}{4}$	Airline focuses on the HSR-inaccessible market only	HSR-accessible market is served by the HSR only, and only the flight–HSR connecting service exists in the connecting market	$\bar{q}_1^A < \hat{q}_1^A$ $\bar{q}_2^R = \hat{q}_2^R$ $\bar{q}_3^{AR} > 0$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\frac{\gamma}{4} < k \leqslant \gamma$	Airline serves both the HSR-inaccessible and HSR-accessible markets, but is not able to cover the connecting market	HSR-accessible market is served by the HSR only, and only the flight–HSR connecting service exists in the connecting market	$\bar{q}_1^A < \hat{q}_1^A$ $\bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AR} > 0$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\gamma < k \leqslant \frac{8-4\gamma-\gamma^2}{4(4-\gamma^2)}$	Airline serves both the HSR-inaccessible and HSR-accessible markets, but is not able to cover the connecting market	Both the airline and HSR serve the HSR-accessible market, but only the flight–HSR connecting service exists in the connecting market	$\bar{q}_1^A < \hat{q}_1^A$ $\bar{q}_2^A + \bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AR} > 0$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\frac{8-4\gamma-\gamma^2}{4(4-\gamma^2)} < k \leqslant \frac{3+\gamma}{2(2+\gamma-\gamma^2)}$	Airline serves all three markets, but is still constrained by hub capacity	Both the airline and HSR serve the HSR-accessible market, but only the flight–HSR connecting service exists in the connecting market	$\bar{q}_1^A \gtreqless \hat{q}_1^A$ $\bar{q}_2^A + \bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AR} > \hat{q}_3^{AA}$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\frac{3+\gamma}{2(2+\gamma-\gamma^2)} < k \leqslant \frac{8+3\gamma}{2(2+\gamma)}$	Airline serves all three markets, but is still constrained by hub capacity	All available services are provided; but the airport is still under capacity constraint	$\bar{q}_1^A \gtreqless \hat{q}_1^A$ $\bar{q}_2^A + \bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AA} + \bar{q}_3^{AR} > \hat{q}_3^{AA}$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$\frac{8+3\gamma}{2(2+\gamma)} < k \leqslant \frac{5+\gamma}{2(1+\gamma)}$	Airport does not face capacity constraint	All available services are provided; but the airport is under capacity constraint	$\bar{q}_1^A < \hat{q}_1^A$ $\bar{q}_2^A + \bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AA} + \bar{q}_3^{AR} > \hat{q}_3^{AA}$	$\overline{W} > \widehat{W}$ $\overline{CS} < \widehat{CS}$
$k > \frac{5+\gamma}{2(1+\gamma)}$	Pre-cooperation market equilibrium	Post-cooperation market equilibrium	$\bar{q}_1^A = \hat{q}_1^A$ $\bar{q}_2^A + \bar{q}_2^R < \hat{q}_2^A + \hat{q}_2^R$ $\bar{q}_3^{AA} + \bar{q}_3^{AR} > \hat{q}_3^{AA}$	$\overline{W} > \widehat{W}$ $\overline{CS} \gtreqless \widehat{CS}$

Given the estimation of γ and the other information provided by Behrens and Pels (2012) – i.e., average fares and traffic volumes of different modes – we can easily obtain α by fitting the linear demand functions of our model. With the average traffic volume per hour, we obtain that α is around 600.

Taking into account the heterogeneity of passengers, we separate the estimates for business and leisure passengers. In particular, we establish that $\gamma = 0.59$ for leisure passengers and $\gamma = 0.825$ for business passengers. If a linear relationship is imposed between the business passenger percentage (φ) and weighted average γ, we have $\gamma = 0.825 - (0.825 - 0.59)\varphi = 0.825 - 0.235\varphi$. A similar approach is adopted to obtain the relationship between φ and the weighted average α.

The procedure to estimate β is very similar to the one used to obtain γ, but with own elasticities instead of cross elasticities. The estimation of δ is straightforward when the other parameters are given.

B.2. Estimation of the cost functions

Brueckner and Spiller (1994) estimate linear marginal cost for airlines, which can be directly used for our purpose. Campos and de Rus (2009) detail the operating statistics and the operating costs for 11 types of high-speed train in four European countries (namely, TGV Reseau, TGV DUPLEX and THALYS in France; ICE-1, ICE-2, ICE-3, ICE 3 Polyc. and ICE/T in Germany; ETR 500 and ETR 480 in Italy; and AVE in Spain). We assume that these high-speed train technologies have an identical cost structure and we estimate this cost structure based on the variability in seat capacities of these train models.

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