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Can entry of high-speed rail increase air traffic? Price competition, travel time difference and catchment expansion

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Abstract

While many empirical studies find that high-speed rail (HSR) exercises a downward pressure on air traffic, several studies observe an increase in air traffic after HSR enters the overlapping markets, especially in long-haul markets (over 1000 km). The paper provides a possible theoretical and empirical explanation on the seemingly conflicted findings. With a model of differentiated price competition, we show that air-rail competition can induce more air traffic after the entry of HSR as long as the air travel time is sufficiently shorter than the HSR travel time. The mixed empirical results could be caused by the failure to incorporate both modes' travel times. Thus, in the empirical part of this paper, we use the difference of HSR and air flight travel times to capture the relative competitiveness of these two competing modes of transport after controlling for the potential catchment expansion effect of HSR. Other route characteristics such as GDP per capita and population of the two endpoint cities, time-invariant route fixed effect and year fixed effect are controlled for in the model as well. Based on a sample of Chinese air routes, our regression analysis confirms the theoretical prediction. In particular, air traffic tends to increase after the entry of HSR if the HSR travel time is over 5 hours longer than air travel time. Otherwise, the air traffic tends to reduce. This implies that a large share of sampled Chinese routes, including both medium-haul and long-haul routes, may experience an increase in air traffic.

Keywords: Air-rail competition, air-rail travel time difference, catchment expansion, substitution effect, complementary effect, intermodal transport

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1. Introduction

As of October 2019, 47,560 km of high-speed rail (HSR) is in operation world-wide and over 24,000 km is either under construction or planned (UIC, 2019). HSR's impact on overlapping air routes has become a popular research topic. Downward pressure on air traffic, flight frequencies and airfares has been observed in almost all geographical regions, esp. in short/medium-haul markets (Please refer to a comprehensive review by Zhang et al. (2019)). Although most studies found little impact in long-haul markets, substantial air traffic reduction has been observed in certain Chinese markets, e.g. Wuhan-Guangzhou route (1069 km) and Beijing-Shanghai route (1179 km) (Chen, 2017; Fu et al., 2012; Ma et al., 2019). It is suggested that in the context of Chinese markets, Air-HSR competition may extend to routes up to 1300km (Zhang and Zhang, 2016).

Most importantly, there are some "counter-intuitive" empirical findings suggesting possible positive impacts on air traffic. For example, significant positive impact of HSR on flight frequency are observed on certain European routes (Bilotkach et al., 2010). Milder or even positive impacts on airline seat capacity are found on spoke-to-spoke routes in France, Spain and Italy (Albalate et al., 2015). Wan et al. (2016) found an increase in airline seat capacity on Chinese routes over 800 km after the entry of 200km/hr HSR services, but traffic reduction was observed after the entry of 300km/hr HSR services. Zhang et al. (2018) discovered an increase in air passenger numbers due to the entry of HSR on Chinese routes over 1000 km. In practice, we observe that Chinese "Big Three" airlines took actions to expand their international markets after massive introduction of HSR services around 2010. China Southern Airlines planned to double the share of international routes, from 18.5% to 40% in 2011 (CAPA, 2011), while China Eastern Airlines planned to introduce new wide-body passenger aircrafts, aiming to raise the percentage of revenues from international routes from 35% to 40% by 2020 (South China Morning Post, 2015). In terms of domestic routes, our data shows that the average length of newly-introduced air routes weighted by seat capacity reaches 1081 km. The yearly average stage length weighted by seat capacity grew year by year, from 1081 km in 2008 to 1150 km in 2015. These two facts suggest that carriers are inclined to explore long-haul markets when facing increasingly strong competition from HSR. These observations, together with the empirical findings, are especially disturbing as HSR is believed to reduce emission in inter-city transportation markets by replacing higher-emission air services with lower-emission HSR services.

The literature fails to provide any reconciliation on the seemingly conflicted empirical results, neither theoretically nor empirically. To our knowledge, all existing theoretical works about air-rail competition predicts a reduction in air traffic after the entry of HSR, and hence none of them demonstrates a possible air traffic increase in certain constellations (see Zhang et al. (2019) for a review). To provide a clearer guidance for policy makers, one must better understand the mechanism behind and the empirical reasons for the mixed empirical findings.

Thus, this paper has two major objectives. The first objective is to provide a possible theoretical explanation on the mixed empirical findings. Our theoretical model is most relevant to D'Alfonso et al. (2015) who assume Cournot (quantity) competition between the airline and HSR. Our model uses the similar basic settings but assumes differentiated Bertrand (price) competition. Quantity competition has been widely assumed in theoretical modeling of airline competition. Traditionally, this assumption has been supported by Brander and Zhang's (1990) empirical study. However, several studies found that airlines have been deviating from Cournot behavior, using more recent data in the U.S. (Fischer and Kamerschen, 2003; Nazarenus, 2011) and Span (Fageda, 2006). In the Chinese aviation market, the focus of our study, airlines have enjoyed higher level of freedom in setting prices as the Civil Aviation Administration of China removed the price floor on air fares in 2013 (Reuters, 2013). This policy change provides more room for price competition. We show that price competition does make a difference. In particular, our model suggests that air traffic may increase after the entry of HSR if the air travel time is sufficiently short relative to the rival HSR's travel time. The air traffic increase mainly results from substantial air fare reduction due to air-rail competition (substitution effect) and creation of new markets when HSR expands the airline's catchment by air-rail intermodal services (catchment expansion effect). Note that air fare reduction may induce more air traffic only when the air mode is sufficiently competitive, say sufficiently faster, compared with the rail mode. In most cases, air mode's speed advantage is marginal when the travel distance is below 1000 km, and therefore, this explains why air traffic increase is more likely to be observed in long-haul routes.

The second objective is to empirically verify the main theoretical predictions on the airlines' adjustment in seat capacity upon the entry of HSR and to demonstrate that both air and HSR's travel times should be taken into account in similar empirical studies. In the relevant empirical literature, almost all the existing studies use only one mode's distance (or travel time) to capture the relative competitiveness of airlines and HSR (see Section 3 for a list of such studies). We believe that this may be one cause of mixed empirical findings even using data of the same market, e.g. China. As demonstrated in Section 4.3, HSR services can be quite competitive relative to air mode in certain long-haul markets (> 1000 km), while air mode can be quite competitive in certain short / medium-haul markets (< 1000 km). Thus, grouping and estimating HSR impacts based on one single mode's distance (mostly air distance) could lead to wrong conclusion and misleading policy suggestion. A better estimation on the impact of HSR entry should include both modes travel times.

Another contribution of the empirical part of this paper is to estimate both substitution effect and catchment expansion (or complementary) effect of HSR simultaneously. To our knowledge, Chen et al. (2019) is the only paper which takes into account both air travel time and rail travel time when estimating the impacts of HSR entry. However, they did not explicitly raise the issue of possible air traffic increase due to air-rail competition. Moreover, their study does not explicitly consider the catchment expansion effect. Liu et al. (2019) try to simultaneously estimate substitution and complementary effects of HSR, but their focus is at airport level instead of route level and therefore they are not able to investigate the heterogeneous substitution effects of different routes. As a result, they cannot characterize air routes which may expect air traffic increase after the entry of HSR.

Our empirical analysis is based on a panel data of Chinese air routes during the 2008-2015 period. We find that air traffic is likely to increase after the entry of HSR if the HSR travel time is over 5 hours longer than the air travel time. Given this cut-off point, a large share (34-56% in varying years) of the sampled air routes facing HSR competition are expected to experience an increase in air traffic, including majority of the routes over 1000 km and a substantial share of medium-haul routes (500 – 1000 km). We also observe strong catchment expansion effect for domestic air routes and Chinese airlines' international routes, whilst traffic of foreign airlines' international routes may negatively associate with HSR's catchment expansion.

The rest of the paper is organized as the follows. Section 2 provides theoretical models to explain why air traffic is not necessarily reduce after entry of HSR. Section 3 states the main hypotheses to be tested in the empirical part and their linkage to the theoretical predictions. Section 4 describes our dataset and variables and Section 5 states the empirical models as well as the regression results. Section 6 concludes the paper.

2. Theoretical analysis

2.1 Base case: City-pair market without catchment expansion

We start with the scenario of one single city-pair market involving two endpoint cities, A and B. Before the entry of HSR, one monopoly airline operates in the city-pair market and after the entry of HSR, HSR provides an overlapping service in the same market as the airline, forming a case of duopolistic competition. Intermodal feeding between air and HSR is abstracted away in this section, because we aim to illustrate how the entry of HSR may induce more air traffic in certain constellations when (1) the airline enjoys market power before the entry of HSR and (2) the airline and HSR are involved in differentiated price competition. This section also explains why similar models with quantity competition (e.g. D'Alfonso et al., 2015) cannot generate this outcome.

Following Dixit (1979), we assume that passengers' utility function is in a quadratic form. This assumption has been widely used in the literature of air-rail competition (e.g. D'Alfonso et al., 2015; Jiang and Zhang, 2014; Socorro and Viecens, 2013). Let q_i refer to the number of trips using mode i, $i \in \{A, H\}$, where A indicates air transport and H indicates HSR. Then, the gross utility of consuming these trips can be written as:

$$U(q_A, q_H) = \alpha_A q_A + \alpha_H q_H - \frac{1}{2}(\beta_A q_A^2 + 2\gamma q_A q_H + \beta_H q_H^2) \quad (1)$$

In equation (1), α_i is a positive parameter which indicates the highest marginal benefit of taking a trip with mode *i* and can also be considered as the strength of mode *i*'s demand. β_i is a positive parameter reflecting the diminishing of marginal utility of mode *i*. The parameter γ represents the substitutability between air and HSR and hence we have $\gamma \geq 0$. When $\gamma = 0$, there is no substitution between these two modes, and hence the airline can be considered as a monopoly which faces the same demand before and after HSR's entry. The passengers maximize the utility net travel time costs while taking into account the budget constraint, and hence they solve the following problem:

$$\max_{q_A, q_H, y} U(q_A, q_H) + y - vT_A q_A - vT_H q_H$$

$$s.t. \;\; p_A q_A + p_H q_H + y \leq I$$

where p_i is the ticket price of mode i, v is passengers' value of time, and T_i is the travel time of mode *i*. In this paper, as we assume the value of time is the same across passengers and modes of transport, in the rest of the paper, we suppress the notation of vT_i into t_i which is linearly associated with the travel time. y is the numeraire indicating the utility of consuming products other than air and HSR trips. I is the given budget reflecting the total resource that the passengers can spend. To guarantee interior solution, we assume $U(q_A, q_H)$ is strictly concave and this assumption requires $\beta_i\beta_j - \gamma^2 > 0$ for any $i \neq j$. This assumption means that the airline and HSR are not perfect substitutes.

Solving for the above problem, we can obtain the inverse demand function and the demand function of each mode $i \in \{A, H\}$:

$$p_i(q_i, q_j) = \alpha_i - t_i - \beta_i q_i - \gamma q_j \quad \text{and} \quad q_i(p_i, p_j) = a_i - b_i(p_i + t_i) + k(p_j + t_j) \qquad (2)$$

where $a_i = \frac{\alpha_i\beta_j - \alpha_j\gamma}{\delta} > 0$, $b_i = \frac{\beta_j}{\delta}$, $k = \frac{\gamma}{\delta}$, and $\delta = \beta_i\beta_j - \gamma^2 > 0$. Note that the first inequality holds because we assume quantity demanded is positive when the full prices are zeros. When we force $q_H = 0$, equation (1) reduces to the utility function before the entry of HSR and solving passengers' problem we can obtain the inverse demand function of the monopoly airline before the entry of HSR:

$$p_A(q_A) = \alpha_A - t_A - \beta_A q_A$$

Before the entry of HSR, the airline maximizes its own profit:

$$\pi_A(q_A) = [p_A(q_A) - c_A] \cdot q_A$$

Here, c_A is the marginal cost of serving one passenger by the airline. Without loss of generality, c_A and c_H, the marginal cost of HSR, are normalized to zero so that we can focus on the travel time difference between air and HSR in the rest of the paper. Given that the airline is a monopolist, choosing quantity and choosing price will generate the same equilibrium outcome. Throughout the paper, we use superscript M to indicate monopoly case before the entry of HSR. After taking the first-order condition of the airline's profit, the monopoly quantity and price are:

$$q_A^M = \frac{\alpha_A - t_A}{2\beta_A} \qquad (3)$$

$$p_A^M = \frac{\alpha_A - t_A}{2} = \beta_A q_A^M \qquad (4)$$

After the entry of HSR, the profit of mode i can be written as a function of quantities in equation (5) or prices in equation (6):

$$\pi_i(q_i, q_j) = p_i(q_i, q_j) \cdot q_i \qquad (5)$$

$$\pi_i(p_i, p_j) = p_i \cdot q_i(p_i, p_j) \tag{6}$$

Each mode of transport maximizes its own profit by choosing quantity or price.[1] The rest of the paper mainly compares the airline's equilibrium quantities after HSR entry with the case of no HSR entry.

(1) Quantity competition

After taking the first-order condition of $\pi_A(q_A, q_H)$ with respective to q_A, we obtain the following:

$$\frac{\partial \pi_A(q_A, q_H)}{\partial q_A} = \frac{\partial p_A(q_A, q_H)}{\partial q_A} q_A + p_A(q_A, q_H) = -\beta_A q_A + p_A(q_A, q_H) = 0 \tag{7}$$

From (7), it is straightforward to see that $p_A^C = \beta_A q_A^C$ where the superscript C indicates that the airline's strategic variable is quantity. Based on equations (3) and (7), we rewrite the airline's best-response function into a function of monopoly airline quantity (q_A^M):

$$q_A^C(q_H) = \frac{\alpha_A - t_A}{2\beta_A} - \frac{\gamma}{2\beta_A} q_H = q_A^M - \frac{\gamma}{2\beta_A} q_H \leq q_A^M \tag{8}$$

As the quantity of HSR is non-negative, one can easily see from the inequality (8) that the entry of HSR will reduce the airline's quantity if the airline chooses quantity to maximize its profit. The quantity level will get back to the monopoly quantity only when $q_H = 0$. Moreover, from equation (4), we have $p_A^C - p_A^M = \beta_A(q_A^C - q_A^M) \leq 0$. That is, the airline will reduce price below the monopoly level after the entry of HSR. We then obtain Proposition 1.

Proposition 1: If the airline's strategic variable is quantity, after the entry of HSR, both air traffic and airfare decrease.

Note that Proposition 1 holds regardless the HSR's decision variable. The above findings have been published by D'Alfonso et al. (2015). However, this quantity competition setting fails to provide an explanation for the increased airline traffic empirically observed in certain markets.

(2) Price competition

If the airline's strategic variable is price, the first-order condition with respect to p_A will generate:

[1] Our findings hold qualitatively with welfare-maximizing HSR as well.

$$\frac{\partial \pi_A(p_A, p_H)}{\partial p_A} = q_A(p_A, p_H) + \frac{\partial q_A(p_A, p_H)}{\partial p_A} p_A = q_A(p_A, p_H) - b_A p_A = 0 \quad (9)$$

Let superscript B indicate the case where the airline chooses price to maximize profit. We can then rewrite (9) into

$$p_A^B = \frac{q_A^B}{b_A} = \left(\beta_A - \frac{\gamma^2}{\beta_H}\right) q_A^B$$

Using equations (2) and (3), we have:

$$p_A^B = \alpha_A - t_A - \beta_A q_A^B - \gamma q_H = 2\beta_A q_A^M - \beta_A q_A^B - \gamma q_H$$

Equating the above two expressions of p_A^B, we can obtain the "best response" of the airline's quantity as a function of q_H:

$$q_A^B(q_H) = \frac{q_A^M - \frac{\gamma}{2\beta_A} q_H}{1 - \frac{\gamma^2}{2\beta_A \beta_H}} \quad (10)$$

The numerator of the right-hand side of equation (10) equals to $q_A^C(q_H)$ which is less than q_A^M, but the denominator is in between zero and one, and as a result, $q_A^B(q_H) > q_A^M$ may occur provided that q_H is sufficiently low. In particular, the entry of HSR will increase air traffic if and only if $q_A^B > \frac{\beta_A}{\gamma} q_H$. Compared with the case of choosing quantity, when the airline chooses price, it tends to be more aggressive and substantially reduce price, inducing more air travel demand. As shown in Appendix A, the condition $q_A^B > \frac{\beta_A}{\gamma} q_H$ is likely to hold when the air travel time is sufficiently short relative to the rail travel time. In terms of air fare, using equations (2), (4) and (10), we can also show $p_A^B - p_A^M \leq 0$, where the equal sign holds when $\gamma = 0$ (See Appendix A). That is, similar to the quantity competition case, the airline will reduce price after the entry of HSR.

Singh and Vives (1984) have explained why quantity competition and price competition generate different equilibrium outcomes. Indeed, the rivals' *perceived* demand functions are more sensitive to their own prices in Bertrand competition than in Cournot competition. Taking the airline as an example, under Bertrand competition, the airline's perceived demand function, denoted as $Q_A^B(p_A, p_H)$, is the same as the demand function in Eq. (2). That is,

$$Q_A^B(p_A, p_H) = a_A - b_A(p_A + t_A) + k(p_H + t_H)$$

However, under Cournot competition, the airline knows that HSR's strategic variable is quantity, instead of price. Thus, the airline takes HSR's quantity, instead of price, as given when making decisions. Therefore, the *perceived* demand function under Cournot competition, denoted as $Q_A^C(p_A, q_H)$, can be obtained by rearranging its inverse demand function in Eq. (2). As a result, we have:

$$Q_A^C(p_A, q_H) = \frac{\alpha_A - t_A - p_A - \gamma q_H}{\beta_A}$$

Note that when HSR's quantity is zero, the airline's *perceived* demand function in Cournot will be reduced to the airline's monopoly demand function before the entry of HSR:

$$Q_A^C(p_A, q_H = 0) = Q_A^M(p_A) = \frac{\alpha_A - t_A - p_A}{\beta_A}$$

Then, it can be seen that the slope of perceived demand function is $-b_A$ in Bertrand and $-1/\beta_A$ in Cournot and monopoly case, and it is straightforward to see that $-b_A < -1/\beta_A$. That is, the airline perceives a more elastic demand function in Bertrand than in Cournot. As a result, Bertrand competition leads to lower prices and higher quantities than Cournot competition. While Cournot quantity is below monopoly quantity, Bertrand quantity can be far above Cournot quantity and exceed monopoly quantity. This occurs when air is sufficiently competitive (reflected by the travel time) relative to rail.

Figure 1 illustrates why air traffic may increase after the entry of HSR under price competition but not quantity competition. As illustrated in Figure 1(a) and explained above, the perceived demand function under Cournot competition, $Q_A^C(p_A, q_H)$, is a parallel inward shift of monopoly demand function, $Q_A^C(p_A)$, as the slope of the perceived demand function is the same as the monopoly demand function. The amount of the shift depends on HSR's quantity q_H. As a result, the airline's *perceived* marginal revenue (the red dashed lines) of any given level of q_H is below the marginal revenue of the monopoly case. This implies that at any positive level of q_H, the airline's revenue-maximizing (equivalent to profit-maximizing in our setting) quantity under Cournot competition $q_A^C(q_H)$ is below the monopoly quantity q_A^M.

[Insert Figure 1 here.]

However, when price competition is in concern, the entry of HSR changes both the slope and intersections of the airline's demand function (Figure 1(b)). The airlines' perceived demand under price competition can be rewritten into:

$$Q_A^B(p_A, p_H) = b_A(\alpha_A - t_A) - k(\alpha_H - p_H - t_H) - b_A p_A$$

While the entry of HSR increases the slope ($b_A > 1/\beta_A$), making demand more sensitive to airfare, it also affects the market base of potential passengers when air fare is zero, i.e. the intercept on the q_A-axis. The intercept can be larger or smaller than the intercept of the monopoly demand function. On one hand, the introduction of HSR service induces travel demand, which is reflected by $b_A(\alpha_A - t_A) > (\alpha_A - t_A)/\beta_A$. On the other hand, the airline may lose market base due to the competition from HSR, which is reflected by $k(\alpha_H - p_H - t_H)$. As a result, if the competitiveness of HSR is quite weak (i.e. high t_H, p_H and low α_H), the intercept of $Q_A^B(p_A, p_H)$ is more likely to exceed the intercept of $Q_A^M(p_A)$. When this occurs at p_H, the airline's best response is to set price such that the corresponding quantity $q_A^B(p_H)$ is above the monopoly quantity q_A^M. Otherwise, $q_A^B(p_H)$ is below q_A^M.

The above discussion leads to Proposition 2. Note again that Proposition 2 holds regardless the HSR's strategic variable.

Proposition 2: If the airline's strategic variable is price, after the entry of HSR, the airfare will decrease but air traffic may increase when the air travel time is sufficiently short relatively to the rail travel time.

Proof: See Appendix A.

Corollary 1: If both the airline and HSR compete in price, the air traffic will increase if and only if $\frac{\alpha_A - t_A}{\alpha_H - t_H} > \frac{2\beta_A^2\beta_H}{\gamma(3\beta_A\beta_H - \gamma^2)}$.

Proof: See Appendix B.

Corollary 1 suggests that the air traffic is likely to increase when the air mode is sufficiently competitive relative to HSR. In particular, an increase in air traffic requires that the air mode has short trip time (t_A) or high passenger willingness-to-pay (α_A), such that $\frac{\alpha_A - t_A}{\alpha_H - t_H}$ can be sufficiently large. Note that in most of the cases, as the travel distance increases, t_A is likely to be substantially lower than t_H, and as a result the condition stated in Corollary 1 can be easily satisfied in long-haul markets.

2.2 Three-city network with catchment expansion

An HSR line usually links several cities and some of these cities can be relatively small and have limited air services. Thus, the entry of HSR commonly not only provides a substitute of the air mode in the overlapping markets, but also expands the air mode's catchment. This complementary feeding effect could also raise air traffic beyond the effect of price competition as mentioned in Section 2.1. In this section, we extend the previous model of price competition to incorporate the case of catchment expansion.

As illustrated in Figure 2, here we consider three cities, as indicated by nodes A, B and C, and city C has no airport. Before the entry of HSR, the monopoly airline only serves between nodes A and B (market 1). We assume the costs of traveling between city B and city C and between city A and city C are unaffordable for passengers, and therefore there is almost no traffic between city B and city C (market 2) and between city A and city C (market 3).

[Insert Figure 2 here.]

The entry of HSR links city C to city B and hence creates markets 2 and 3. HSR is the only operator on segment BC but both the airline and HSR operate on segment AB. In market 3, the passengers have two alternatives: (1) a direct HSR service throughout the entire journey with probably a stop at city B and (2) an air-rail intermodal service with an air flight on segment AB and a train ride on segment BC which requires a transfer at city B.[2] Following Section 2.1, in market 2, HSR is the only operator and hence its demand function is:

$$q_{2H}(p_{2H}) = \frac{\alpha_{2H} - t_{2H} - p_{2H}}{\beta_{2H}} \tag{11}$$

where t_{2H} is the rail travel time in market 2 and p_{2H} is the rail ticket price in market 2.

In markets with two alternative modes of transport, market 1 and market 3, the inverse demand function and demand function of mode i in each market $m \in \{1,3\}$ are:

$$\begin{aligned} \rho_{mi}(q_{mi}, q_{mj}) &= \alpha_{mi} - \beta_{mi} q_{mi} - \gamma_m q_{mj} \\ q_{mi}(\rho_{mi}, \rho_{mj}) &= a_{mi} - b_{mi} \rho_{mi} + k_m \rho_{mj} \end{aligned} \tag{12}$$

[2] This model relates to the work by Xia et al.'s (2019). Xia et al.'s (2019) model competition between an air-HSR intermodal service and a non-stop air service in the same city-pair market. In our market 3, we model competition between an air-HSR intermodal service and a direct HSR service. Another difference is that Xia et al. (2019) only model one origin-destination market and abstract away all the other related markets, but we include market 1 and market 2, together with market 3.

Where $a_{mi} = \frac{\alpha_{mi}\beta_{mj}-\alpha_{mj}\gamma_m}{\delta_m} > 0$, $b_{mi} = \frac{\beta_{mj}}{\delta_m}$, $k_m = \frac{\gamma_m}{\delta_m}$, and $\delta_m = \beta_{mi}\beta_{mj} - {\gamma_m}^2 > 0$. Let q_{1A} and q_{1H} be respectively the number of air and HSR passengers in market 1. Note that ρ_{mi} is the full price of travelling with mode i in market m, and in market 1, we have $\rho_{1A} = p_{1A} + t_{1A}$ and $\rho_{1H} = p_{1H} + t_{1H}$.

Let q_{3A} and q_{3H} be respectively the number of *air-rail intermodal* passengers and the number of HSR passengers in market 3. In addition to extra air-rail transfer cost (w), air-trail intermodal service requires the passenger to buy one ticket for air segment (p_{1A}) and one ticket for rail segment (p_{2H}). Therefore, the full price of air-rail intermodal will be $\rho_{3A} = p_{1A} + p_{2H} + t_{1A} + t_{2H} + w$. Passengers who take the direct HSR service in market 3 will pay the train ticket (p_{3H}) and incur the rail travel time costs on segment AB (t_{1H}) and segment BC (t_{2H}). Therefore, the full price of direct HSR service will be $\rho_{3H} = p_{3H} + t_{1H} + t_{2H}$. The air traffic on segment AB (Q_A) will be the sum of air passengers in market 1 and intermodal passengers in market 3, i.e., $Q_A = q_{1A} + q_{3A}$.

Before the entry of HSR, the airline is a monopolist and only operates in market 1 and therefore its equilibrium quantity and price will be $Q_A^M = q_{1A}^M = \frac{\alpha_{1A}-t_{1A}}{2\beta_{1A}}$ and $p_{1A}^M = \beta_{1A}q_{1A}^M$. After the entry of HSR, the airline chooses p_{1A} to maximize the following profit:

$$\begin{aligned}\pi_A(p_{1A}, p_{1H}, p_{3H}) &= p_{1A} \cdot \left[q_{1A}\left(\rho_{1A}, \rho_{1H}\right) + q_{3A}\left(\rho_{3A}, \rho_{3H}\right)\right] \\ &= p_{1A} \cdot \left[q_{1A}\left(p_{1A} + t_{1A}\,, p_{1H} + t_{1H}\right) + q_{3A}\left(p_{1A} + p_{2H} + t_{1A} + t_{2H} + w, p_{3H} + t_{1H} + t_{2H}\right)\right]\end{aligned} \tag{13}$$

After taking the first-order condition of (13) with respect to p_{1A}, we can obtain:

$$q_{1A}^B + q_{3A}^B = p_{1A}^B(b_{1A} + b_{3A}) \tag{14}$$

Similar to Section 2.1, as $p_{1A}^B = 2\beta_{1A}q_{1A}^M - \beta_{1A}q_{1A}^B - \gamma_1 q_{1H}$, equation (14) can be rewritten into:

$$q_{1A}^B = \frac{q_{1A}^M - \frac{\gamma_1}{2\beta_{1A}}q_{1H}}{1 - \frac{{\gamma_1}^2}{2\beta_{1A}\beta_{1H}}} + \frac{\delta_1\left(b_{3A}p_{1A}^B - q_{3A}^B\right)}{\beta_{1A}\beta_{1H} + \delta_1} \tag{15}$$

The first term of (15) is the same as (10) and it indicates the substitution effect of HSR on the overlapping market 1. As noted in Section 2.1, this term can be larger or smaller than the traffic before HSR entry (q_{1A}^M) depending on q_{1H}. The second term of (15) relates to the newly created market 3 which can be positive or negative. As the demand function (12) suggests $q_{3A}^B = a_{3A} -$

$b_{3A}(p_{1A}^B + p_{2H} + t_{1A} + t_{2H} + w) + k_3(p_{3H} + t_{1H} + t_{2H})$, the second term is likely to be negative when market 3 is strong (large a_{3A}) or the direct HSR service is not competitive compared to the intermodal service due to high p_{3H} and t_{1H}. That is, when the air-rail intermodal service is strong, the airline may raise price in market 1 to exploit profit in market 3, imposing a downward pressure on the air traffic in market 1. That is, $p_{1A}^B - p_{1A}^M > 0$ may occur if q_{3A}^B is large enough (See Appendix C), which is different from the case of single city-pair market without catchment expansion. Otherwise, the air-rail intermodal service may impose an upward pressure on the air traffic in market 1 and will further reduce air fare.

However, if we consider the total air traffic on segment AB, we have:

$$Q_A^B = q_{1A}^B + q_{3A}^B = \frac{q_{1A}^M - \frac{\gamma_1}{2\beta_{1A}} q_{1H}}{1 - \frac{{\gamma_1}^2}{2\beta_{1A}\beta_{1H}}} + \frac{\delta_1 b_{3A} p_{1A}^B + \beta_{1A}\beta_{1H} q_{3A}^B}{\beta_{1A}\beta_{1H} + \delta_1} \quad (16)$$

As the second term of (16) is positive, it suggests that the newly created air-rail intermodal service always imposes a positive complementary effect on the air traffic on segment AB, after the substitution effect in the overlapping market 1 (the first term) is removed. The above discussion leads to Proposition 3 and Corollary 2.

Proposition 3: If the airline's strategic variable is price, after the entry of HSR, the air fare may increase if the complementary effect is very strong, leading to a reduction in air traffic in market 1, i.e. $q_{1A}^B < q_{1A}^M$. Air traffic on segment AB may increase, i.e. $Q_A^B > Q_A^M$, if the complementary effect is sufficiently large or the competition from HSR raises air traffic in market 1.

Proof: See Appendix C.

Corollary 2: When $p_{1A}^B - p_{1A}^M > 0$, it implies $q_{1A}^M - q_{1A}^B > 0$. When $q_{1A}^M - q_{1A}^B < 0$, it implies $p_{1A}^B - p_{1A}^M < 0$.

Proof: See Appendix D.

To understand how different air and rail trip times affect equilibrium air traffic before and after the entry of HSR, we further assume the HSR also chooses prices to maximize its profit:

$$\pi_H = p_{1H} \cdot q_{1H}(\rho_{1A}, \rho_{1H}) + p_{2H} \cdot [q_{2H}(p_{2H}) + q_{3A}(\rho_{3A}, \rho_{3H})] + p_{3H} \cdot q_{3H}(\rho_{3A}, \rho_{3H})$$

To obtain tractable results for comparative static analysis, we further remove asymmetry in the slope of demand functions across markets. In particular, we assume for each market m, $\beta_{mi} = \beta_i$ and $\gamma_m = \gamma$, and then we have $b_{mi} = b_i$, $k_m = k$ and $\delta_m = \delta$. Table 1 lists the impact of increasing various travel times and air-rail transfer time on the air fare and air traffic in various markets (Refer to Appendix E for the proof). Note that $\gamma < \beta_H$ normally holds as $\delta > 0$, unless $\beta_H \gg \beta_A$, implying that the passengers are far more sensitive to air fare than HSR price ($b_A \gg b_H$).

[Insert Table 1 here.]

From Table 1, we can conclude that keeping all the other factors constant, an increase in air travel time forces the airline to reduce post-entry air fare (p_{1A}^B) but the post-entry air traffic (q_{1A}^B, Q_A^B) will reduce as the air mode becomes less competitive relative to HSR, leading to higher chance of having air traffic drop below the pre-entry level (q_{1A}^M, Q_A^M). However, as the pre-entry air fare (p_{1A}^M) reduces faster than post-entry air fare, an increase in air travel time raises the chance that the post-entry air fare becomes larger than the air fare before HSR entry. However, given fixed air travel time, as rail travel time in market 1 increases, both post-entry air traffic and air fare tend to increase due to improved relative competitiveness of air mode, which also raises the chance of having post-entry air traffic exceeding pre-entry air traffic. Whilst, as suggested by Corollary 2, as long as the post-entry air traffic in market 1 exceeds the pre-entry air traffic, the post-entry air fare should be below the pre-entry air fare. Given the air travel time, a reduction in the feeding leg's HSR travel time (t_{2H}) is likely to boost the air traffic in segment AB in normal cases (unless the passengers are far more sensitive to air fare than HSR price). Reducing air-rail transfer time (w) will in general have similar effects as reducing t_{2H}. Proposition 4 summarizes the key message from Table 1.

Proposition 4: When the airline and HSR involve in price competition, the entry of HSR is likely to increase air traffic on segment AB ($Q_A^B - Q_A^M > 0$) when t_{1A}, t_{2H} and w are sufficiently small relative to t_{1H}. Similar condition will lead to strong complementary effect (large q_{3A}^B). The substitution effect is likely to raise air traffic in market 1 ($q_{1A}^B - q_{1A}^M > 0$) when t_{1A} is sufficiently small relative to t_{1H}, t_{2H} and w.

Proof: See Appendix E.

3. Hypotheses for empirical verification

The rest of the paper empirically verifies some of the main findings of the theoretical analysis in the context of China. Our main theoretical findings largely hold regardless HSR's decision variable, since the key idea holds as long as the airline's decision variable is price according to Propositions

2 and 3. Thus, despite that the pricing of Chinese HSR is not market-based, our theoretical prediction can still be used to explain air traffic increase in certain long-haul Chinese domestic routes.

Our focus is on airlines' response to HSR's parallel entry into the air routes (market 1) which forms direct competition with the airline or HSR's serial entry into rail links (market 2) which connects to the focal air routes and potentially expands the air services' catchment as well as the air-HSR intermodal options (market 3). According to the theoretical predictions derived from Section 2, the impact of HSR entry should be determined by not only the air travel time but also the rail travel time, or more precisely the relative air-rail travel time.

Among empirical studies which try to capture such feature, most of them measure such heterogeneous impacts of HSR on air traffic based on travel distances which are commonly measured by air route distances (e.g. Chen, 2017; Fu et al., 2014; Li and Loo, 2017; Li et al., 2019b; Wan et al., 2016; Yang et al., 2018; Zhang et al., 2018).[3] For example, Wan et al. (2016) adopt 500 km and 800 km as thresholds for short-, medium- and long-haul routes respectively, whereas Zhang et al. (2018) identify two groups of routes and use 1000 km as threshold. We also observe papers which use HSR distance (Wang et al., 2018) or HSR travel time (Dobruszkes et al. 2014; Li et al. 2019b; Wang et al. 2018) to capture the heterogeneous impacts of HSR. The intuition behind the above approaches is that HSR is more competitive on short-haul routes than long-haul routes, while the air mode is more competitive on long-haul routes than short-haul routes. The drawbacks of such approach are as follows.

First, travel time better captures a mode's competitiveness than travel distance. Given the same rail distance, the travel time can vary substantially as HSR speed and number of stops can vary in route markets and across time. As shown in Figure 3, the scheduled HSR in-vehicle time of the Beijing-Jinan route decreased by around 70 minutes, making the air-rail travel time difference reduce from 151 minutes in 2009 to 51 minutes in 2015. This example suggests that the competitiveness of HSR relative to air flights on the Beijing-Jinan route has been improved considerably, and naturally the impact of HSR in 2009 should be different from that in 2015. In

[3] When estimating the relationship between air traffic and HSR services, many studies only consider distance and travel time as control variables but ignore the fact that the competition between these two modes varies in distance and travel times. For example, Albalate et al. (2015) and Zhang et al. (2017) control for air flight distance and Clewlow et al. (2014) and Zhang et al. (2017) control for HSR travel time.

fact, Wan et al. (2016) do confirm that the impact on air traffic changed in long-haul markets as much faster HSR services were introduced in China.

[Insert Figure 3 here.]

Second, what matters is not one single mode's travel time, but the relative travel time of the air and rail modes. Routes with similar air distance (or air travel time) can have very different rail distances (or rail travel times). Air distances are close to the great circle distances between two endpoints. HSR routes, however, tend to be affected by the physical condition of the surface as well as the need to connect more cities along the rail track and thus rail distances can differ substantially from the great circle distance. As a result, even if the air distances of two routes are the same, the impacts of HSR can differ substantially. For example, Figure 4 shows the in-vehicle times of four routes with close air travel distances (around 580 km) in 2015. The shortest in-vehicle time is 180 minutes (Nanjing-Jinan), whereas the longest one reaches 395 minutes (Hefei-Wenzhou). HSR thus has different levels of threat on air transport in these route markets. Similarly, as shown in Figure 5, routes with close air travel time can vary in HSR travel time.

[Insert Figure 4 and Figure 5 here.]

Given that our dataset does not contain information about air fares, we will indirectly verify some of our theoretical findings by examining the relationship between route-level airline available seats and various travel times, including air travel time (t_{1A}), travel time of HSR that serves the same parallel market as the airlines (t_{1H}) and travel time of HSR that feeds the focal air route (t_{2H}). Following discussions in Section 2, the following hypotheses will be verified in the empirical part, i.e. Sections 4 and 5.

Hypothesis 1: The number of available airline seats will reduce after the entry of HSR if the air travel time is not substantially shorter than the rail travel time in market 1.

Hypothesis 2: The number of available airline seats will increase after the entry of HSR if the air travel time is sufficiently shorter than the rail travel time in market 1.

Hypothesis 3: The number of available airline seats will increase in the size of the catchment which can feed the air routes by HSR and in the length of the air leg (t_{1A}) relative to the rail leg (t_{2H}).

Empirically, we may not perfectly identify HSR's impact on the air traffic in market 1 (substitution effect) and the impact on intermodal traffic in newly created market 3 (complementary effect), because in real life usually when an HSR line launches, it links several cities along the line at the same time (as illustrated in Figure 2). As a result, on many air routes there will be simultaneous entry of parallel as well as serial HSR services. That is, the presence of HSR on an air route (substitution effect) could be associated with the expansion of catchment by HSR (complementary effect). Then to perfectly distinguish these two effects, one must use traffic data which distinguish air passengers fed by HSR from air passengers who only travel between the endpoint cities of the air route. However, to our knowledge, none of the existing secondary data sources provide such detailed traffic data, and as a result our study can only investigate the overall impact of HSR on the air segment, i.e. Q_A of the theoretical model. Thus, in our regression analysis, although we control for air route's catchment expansion by HSR, we still need to be cautious that the rail-air travel time difference may not only capture the substitution effect but possibly certain complementary effect as well. As implied by Proposition 4, both the traffic of the air segment and the air-HSR intermodal traffic q_{3A} can increase as the rail-air travel time difference, $t_{1H} - t_{1A}$, increases. However, due to the complex market structure, the difference of these two terms, substitution effect and complementary effect, can be blurred as well. This is because HSR and air-HSR intermodal routings also compete in market 3, which is theoretically the main contribution of increased q_{3A} when the travel time difference increases. In this sense, it might still be valid to call this partial impact on q_{3A} substitution effect instead of complementary effect, despite that market 3 is created by catchment expansion.

4. Construction of dataset and variables

4.1 Dataset construction

The pre-filtered dataset is formed by all directional non-stop air routes departing from mainland China. That is, all domestic prefectural-level city-pairs in mainland China and all international routes departing from airports in mainland China are included in the initial dataset.[4] The information of the air routes is extracted from OAG Schedules Analyzer. It contains complete scheduled civil aviation flight information including the number of available seats of each flight, operating days and various route attributes, such as air route distances and scheduled flying time.

[4] Domestic routes do not involve Hong Kong, Macau and Taiwan. The routes that depart from airports in mainland China and arrive at Hong Kong, Macau or Taiwan are considered as international routes.

For domestic routes, two directions of the same city-pair are treated as two different routes because HSR service on the two ways of some routes were not open at the same year. For international flights, we only include the air routes that depart from airports in mainland China. Data of the domestic routes are used to quantify HSR's effect on both parallel and feeding air routes while data of the international routes are additionally used to identifying HSR's feeding effect only.

The air service provision is unstable in some low-demand markets. For example, on the Shenyang-to-Fuzhou route, airlines provided service only in 2010 and 2014 during the study period. Carriers' capacity adjustment on such routes can be triggered by many unobservable factors which are irrelevant to HSR's operation. Thus, we only include air routes on which airlines' responses are relatively stable by filtering out routes where air services appear in one year and disappear in the following years randomly. Therefore, we keep air routes which satisfy at least one of the following conditions during our study period:

(i) Air services exist for at least four consecutive years starting from 2008; or
(ii) Air services exist for at least four consecutive years by the end of the study period, i.e. 2015. For example, routes which start air service in 2012 and the service continues till 2015 will be included in our dataset.

In the end, the cleaned dataset contains 2,236 domestic air routes and 531 international air routes, covering 168 prefectural-level cities in mainland China (Table 2). The majority (68% domestic and 50% international) of the selected routes were constantly served by airlines during the whole eight-year study period. Among routes that have less than 8 years' air service, the numbers of new domestic and international routes are 641 and 240 respectively, while the numbers of quitted domestic and international routes are 65 and 32 respectively (not shown in the table). The number of newly served routes is much larger than the quitted routes, because the opening of new airports provides chances for airlines to add service on some new routes. After the filtering process, we obtain a panel data of annual observations from 2008 to 2015. Each observation represents a route-year pair.

[Insert Table 2 here.]

4.2 HSR entry in Chinese mainland

Chinese HSR data are extracted from the National Rail Timetable of China (July edition, 2008-2015) which includes all the stops made by each train, its service frequency as well as departure and arrival times at each station. The timetable has several editions each year due to adjustment of service schedule throughout a year. Considering that the majority of newly constructed HSR lines are either operated in the beginning of July or at the end of December, we follow Liu et al. (2019) and use the July editions. Since the July editions can capture all HSR entries till the end of July, most new entries recorded in later editions of a year occurred near the end of the year and hence may have limited impact on the year's air traffic. Thus, if an HSR service starts after July, its entry will be counted in the following year instead of the current year. In this paper, the unit of observations is prefecture-level routes. That is, the two endpoints of a route are prefecture-level cities. We merge all the HSR stations in a prefecture-level city together and derive the daily service frequency and average in-vehicle time for each route.

As of 1st October 2019, China has 31,043 km HSR lines in operation, accounting for 65.2% of the world's total HSR length (UIC, 2019). Our sampling period covers a rapid growing stage of China's HSR network. As a measure of boosting economy after the global financial crisis, the Chinese Government started heavy investment in HSR since 2008 and the back-bone network of four north-south routes and four east-west routes has been formed by 2015.

During the study period, 360 air routes in our dataset encountered HSR entry. Table 3 summarizes the number of air routes facing competition from parallel HSR services in each year. The number of air routes with the presence of HSR serves increased almost every year except 2012. In 2012, the number of routes facing HSR competition decreased to 163, probably because of the serious crash on the Yong-Wen HSR line in 2011. After the accident, the Ministry of Railway required majority of the HSR services to reduce the maximum operating speed of HSR trains. In particular, trains of 350 km/h were slowed to 300 km/h, 250 km/h to 200 km/h, and 200 km/h to 160 km/h. Trains running on upgraded conventional lines were substantially affected, as their speed was reduced to 160 km/h at maximum. For example, the speed reduction made Beijing West - Chengdu line much less attractive in terms of the total travel time and ticket price. In 2012, HSR operator cut HSR services on this line and replaced them with additional conventional rail services. For this reason, fewer sampled routes were served by HSR in 2012.

[Insert Table 3 here.]

4.3 Variable construction

As pointed out by Behrens and Pels (2012) and discussed in Section 3, travel time is one of the most important determinants of transport modal choice. We identify the heterogeneity of HSR's impacts on different air routes by considering both modes' scheduled in-vehicle times instead of travel distance or travel time of one single mode.

When estimating the impact on air routes with parallel HSR services, following Chen et al. (2019), we specifically use the travel time difference that is equal to HSR's *average* scheduled in-vehicle time minus airlines' *average* scheduled in-vehicle time to capture the competitiveness of air mode relative to the rail mode. Based on the travel time difference, we construct a set of nine 0-1 dummy variables, Tdiff_1 ~ Tdiff_9, each representing a certain range of travel time difference. As indicated in Table 4, Tdiff1 indicates air routes with parallel HSR service and with rail-air travel time difference below two hours. That is, Tdiff_1 = 1 if an observation has HSR service and the rail-air travel time difference is less than two hours, and Tdiff_1 = 0 if an observation has either no HSR service or the rail-air travel time difference is more than two hours. Tdiff_2 indicates air routes with parallel HSR service and with rail-air travel time difference between two and three hours. The detailed ranges of travel time differece of each dummy variable are shown in Table 4. Note that for majority of the observations, there is no HSR presence on the parallel route and these observations will have zero values for all the nine dummy variables.

[Insert Table 4 here.]

As shown in Table 4, the mean, minimum and maximum air route distances all increase as the travel time difference increases, suggesting that air mode is more competitive than HSR as distance increases overall. However, the distributions of air route distances are highly overlapped across all the levels of travel time difference. For example, the minimum air distance of observations with travel time difference above nine hours (576.5 km) is still below the maximum air distance of observations with travel time difference below two hours (661 km). The travel time difference of long-haul routes (air distance > 1000 km) also has a wide range, from 3 hours to over 9 hours. Therefore, it is not necessarily the case that HSR is competitive in short-haul routes and not competitive in long-haul routes, and as a result one may obtain misleading results if the heterogeneous impacts of HSR are identified only based one single mode's distance (or travel time).

We further identify the impact of HSR on complementary air routes as the entry of HSR could expand air route's catchment area. The entry of HSR can improve the linkage between the endpoint cities of the air route and the nearby cities without a similar air service. With faster access to the enpoint city of the air route, the catchment area of the air route is expanded. That is, HSR can help with feeding more traffic from nearby cities to the air route. To capture the effect of catchment expansion, we first define a set of HSR feeding cities of each air route. As indicated in Figure 6, for a particular air route between endpoint cities A and B, an HSR feeding city refers to any nearby city that is linked to city A (city B) by direct HSR services and does not have any non-stop air flight linking to the other endpoint city B (city A).[5] That is, taking the air route AB in Figure 6 as the focal route, city C is an HSR feeding city of route AB since there is no non-stop flight between city C and city B and hence passengers in city C must take certain ground transport to city A before taking flights to city B. Certainly, there might be other surface modes which link city C and city A, but HSR provides one additional and potentially faster alternative, and thus improves the connectivity between city C and city A. As a result, HSR may increase the attractiveness of C-A-B intermodal routing relative to other options (if any),[6] which potentially expands the catchment of route AB. On the other hand, city D is not considered as an HSR feeding city of route AB since there are non-stop flights between city D and city A. City E is not an HSR feeding city either, since it is not linked to city A by HSR.

[Insert Figure 6 here.]

Another issue associated with the definition of HSR feeding city is the distance between the feeding city and the endpoint cities of an air route. Due to the size of the HSR network in mainland China, some identified feeding cities can be over 7 hours away from the endpoints of the focal air route. It is hard to argue that HSR can effectively feed traffic from these faraway cities to the focal air route. Therefore, we further filter out the feeding cities that are too far away from the endpoints of the focal air route. In particular, we set several thresholds of HSR travel time between the feeding cities and their nearest endpoint city of the focal air route. For each threshold, we conduct regression analysis by keeping feeding cities of which the HSR travel time between the feeding city and the air route's endpoint is below the threshold. The thresholds range from 0.5 hours to 3 hours with an increment of 0.5 hours, i.e. 0.5 hours, 1 hour, 1.5 hours, …, 3 hours. Some feeding cities have HSR links to both endpoints of the focal air routes. In this case, we consider

[5] In defining "direct" HSR links, we do not require that there are no stops between two endpoints. As long as passengers do not need to get off the train, the HSR links are regarded as direct.
[6] "Other options" could be air-air connecting routings in which passengers depart from city C and transit at any city other than B.

the nearest endpoint in terms of HSR travel time. After identifying the effective HSR feeding cities, we calculate the total population of the feeding cities, denoted as FeedPop. This variable is used to measure the size of the air route's catchment expansion due to HSR.

In addition to travel time difference and catchment expansion, our regression analysis also utilizes several other variables. Their notations and definitions are available in Table 5. Their descriptive statistics are shown in Table 6.

[Insert Table 5 and Table 6 here.]

5. Econometric models and regression results

5.1 Econometric models

We first introduce the main model that simultaneously identifies the substitution and complementary effects of HSR on the number of available seats of air transport. Note that only domestic air routes are included in the estimation of main model, since none of the international air services encounter parallel HSR operations. The main model is specified in the following equation.

$$Seat_{it} = \beta_0 + \sum_{m=1}^{9} \beta_{\mathrm{m}}(HSR_{it} \times Tdiff\_m_{it}) + \beta_{10}(HSR_{it} \times HSRFreq_{it}) + \beta_{11}(FeedPop_{\mathrm{it}} \times AirTime_{\mathrm{it}}) + \beta_{12}RoutePop_{\mathrm{it}} + \beta_{13}RouteGDP_{\mathrm{it}} + route_i + year_t + \varepsilon_{it} \qquad \text{(M1)}$$

In Eq.(M1), the impact of the entry of parallel HSR services (substitution effect) on airlines' seat capacity is identified by the first two interactions with the 0-1 dummy variable HSR_{it}, since we compare the airline seats between air routes with and without HSR services. The nine coefficients $\beta_1 \sim \beta_9$ capture the effect of heterogeneous competitiveness of air mode relative to HSR which is measured by rail-air travel time difference. For example, β_1 reflects the substitution effect when the air mode is the least competitive relative to HSR, as the difference between HSR travel time and air travel time is less than 2 hours. Whilst, β_9 reflects the substitution effect when the air mode is the most competitive relative to HSR, as the air mode is over 9-hour faster than HSR. According to Section 3, we expect that the coefficients at lower levels of rail-air travel time difference (such as β_1) are negative but the coefficients at higher levels of rail-air travel time difference (such as β_9) are positive. In the model, we also consider HSR frequency as frequency is one key quality aspect of scheduled transportation services. Coefficient β_{10} captures the impact of HSR service frequencies and is expected to be negative, as after controlling for the difference of travel times, the competitiveness of HSR increases in its service frequency.

The interactive term $FeedPop_{\text{it}} \times AirTime_{\text{it}}$ captures the impact of serial HSR entry on complementary air routes due to the presence of air-HSR intermodal routings. As $FeedPop_{\text{it}}$ measures the total population of effective HSR feeding cities, we expect the demand for air-HSR intermodal services and hence seats on the focal air route will increase as $FeedPop_{\text{it}}$ increases. Moreover, intuitively, the attractiveness of the air-HSR intermodal service will increase as the travel time of the air leg increases relative to the HSR feeding leg. If the air leg is very short relative to the HSR leg, the time saving of the air leg would not justify the cost and inconvenience of the intermodal service compared with other alternatives. This reasoning is consistent with Table 1 and Proposition 4, as controlling for the travel time of air leg (t_{1A}), the intermodal traffic (q_{3A}^{B}) is likely to decrease in the HSR feeding time (t_{2H}). Since $FeedPop_{\text{it}}$ is calculated based on a prespecified threshold distance between feeding cities and the air route's endpoint cities, the HSR feeding time in the empirical model is relatively fixed. As a result, we interact $FeedPop_{\text{it}}$ with air travel time ($AirTime_{\text{it}}$) to examine how the travel time of the air leg is associated with the catchment expansion effect of HSR after controlling for the air-HSR competition on the parallel route. Therefore, we expect coefficient β_{11} to be positive.

Finally, $RoutePop_{it}$ and $RouteGDP_{it}$ are control variables which measure the potential market size of each air route. We expect the demand for airline seats to increase in the endpoints' population and income (per capita GDP) and therefore β_{12} and β_{13} are expected to be positive. Route fixed effects and year fixed effects are included to control for unknown characteristics specific to individual routes and individual years respectively.

Recall the discussion in Section 3. The estimated coefficients $\beta_1 \sim \beta_9$ in Eq.(M1) may capture not only impact on passengers in the endpoint cities (substitution effect) but also possibly part of the catchment expansion effect due to competition between air-HSR intermodal routings and pure HSR routings from the feeding cities. To be complete and cautious, we further estimate two variations of Eq.(M1). In Eq.(M2), we remove the variables which is used to capture the catchment expansion effect, $FeedPop_{\text{it}} \times AirTime_{\text{it}}$.

$$Seat_{it} = \beta_0 + \sum_{m=1}^{9} \beta_{\mathrm{m}}(HSR_{it} \times Tdiff\_m_{it}) + \beta_{10}(HSR_{it} \times HSRFreq_{it}) + \beta_{12}RoutePop_{\mathrm{it}} + \beta_{13}RouteGDP_{\mathrm{it}} + route_i + year_t + \varepsilon_{it} \quad \text{(M2)}$$

The purpose of Eq.(M2) is to check how the inclusion of the catchment expansion variable can affect the estimated $\beta_1 \sim \beta_9$. If the exclusion of catchment expansion variables does not substantially change the estimated values of $\beta_1 \sim \beta_9$, we might be more confident to say $\beta_1 \sim \beta_9$ mainly captures the substitution effect.

In Eq.(M3), we drop all the variables that are supposed to capture the substitution effects, i.e. $HSR_{it} \times Tdiff\_m_{it}$ and $HSR_{it} \times HSRFreq_{it}$.

$$Seat_{it} = \beta_0 + \beta_{11}(FeedPop_{\mathrm{it}} \times AirTime_{\mathrm{it}}) + \beta_{12}RoutePop_{\mathrm{it}} + \beta_{13}RouteGDP_{\mathrm{it}} + route_i + year_t + \varepsilon_{it} \quad \text{(M3)}$$

The purpose of estimating Eq.(M3) is to check whether the catchment expansion for air routes without any parallel HSR entry is very different from the full sample. Therefore, when estimating Eq.(M3), we not only use the full sample of domestic routes, but also apply a pure feeding sub-sample by dropping all air routes that have ever faced the presence of parallel HSR operations during the study period. Since substitution effect should not exist on air routes in the subsample, the estimated β_{11} with the subsample should only reflect the catchment expansion effect. Then, if Eq.(M3) with the subsample generates β_{11} similar to the one estimated by Eq.(M1), we will be more confident to say that majority of the catchment expansion effect has been decomposed from substitution effect with Eq.(M1).

Apart from the subsample of the domestic market data, we also estimate Eq.(M3) with the data of international routes to investigate the pure feeding effect on the seat capacity of international air services. Intuitively, the nationality of airlines could affect the results. Chinese airlines may be more attractive to Chinese passengers than foreign passengers. Meanwhile, foreign passengers could find it difficult to purchase HSR tickets and go through the airport-HSR station transfer process in China due to language barriers and unfamiliar environment.[7] That is, most targeting passengers of foreign airlines may experience a much larger air-HSR transfer cost (i.e. parameter *w* in the theoretical model) than the targeting passengers of Chinese airlines. Thus, we

[7] Language barrier may not be an issue at the international airports, but it can be a problem at the rail stations and public transport during the transfer.

expect that HSR is more likely to feed Chinese passengers to international flights than foreign passengers and hence Chinese airlines are more likely to be benefited by HSR's feeding than foreign airlines. Based on this rationale, we estimate Eq.(M3) for Chinese airlines and foreign airlines separately with the data of international routes.

5.2 Empirical results

Tables 7, 8 and 9 present the OLS estimations on domestic routes with various threshold distances of feeding cities, with 0.5 hours and 1 hour in Table 7, 1.5 hours and 2 hours in Table 8, 2.5 hours and 3 hours in Table 9. With each threshold, we conduct three regressions, Eq.(M1) with full sample, Eq.(M3) with full sample and Eq.(M3) with pure feeding subsample. The estimation of Eq.(M2) is listed in the first column of Table 7.

[Insert Tables 7, 8 and 9 here.]

Regarding the impact of HSR entry on parallel air routes, all estimation results of Eq.(M1) as well as Eq.(M2) show that HSR service frequency negatively associates with air traffic, but the entry of HSR may increase or reduce airline seat capacity and the threshold travel time difference is around 5 hours[8]. That is, if the air travel time is less than 5 hours faster than HSR, the airlines' available seats will reduce after the entry of HSR. Moreover, as the travel time difference increase from less than 2 hours to 5 hours, the negative impact of HSR diminishes (from a reduction about 97,000 seats to a reduction about 10,000 seats). Conversely, if the HSR service takes more than 5 hours longer time than air transport, airlines' seat capacity will increase. As the travel time difference increase from 5 hours to over 9 hours, the positive impact of HSR inflates (from an increase about 18,000 seats to an increase about 62,000 seats). The above finding is very robust as it clearly holds and the magnitudes of the estimated coefficients ($\beta_1 \sim \beta_9$) are very close across all thresholds of feeding city distances and regardless the removal of catchment expansion variable. This result is consistent with our theoretical prediction in Section 2 and the estimation by Chen et al. (2019). Chen et al. (2019) use a hierarchical model to establish a functional relationship between route-level air passenger number and rail-air travel time difference. They also find that the impact

[8] We also conducted the regression using scheduled flight frequency as the dependent variable for robustness check and obtained results consistent to those shown in Tables 7, 8 and 9. Considering the length of our paper, these results are available upon request.

of HSR declines as the travel time difference increases.[9]

Table 10 counts the number of routes with travel time difference below 5 hours and above 5 hours respectively in each year of study. Across all air distances, at least 34.6% of the relevant air routes are expected to see an increase in air traffic after controlling for various other factors. This share has been increased to over 50% in 2014 and 2015, because long-haul HSR services opened quickly in these two years as all major HSR corridors in China became well connected with each other and hence formed a complex network during these two years.

[Insert Table 10 here.]

Based on Table 10, we can partly reconcile the mixed empirical findings on long-haul routes in the literature. Wan et al. (2016) and Zhang et al. (2018) find an increase in air traffic in Chinese long-haul routes after entry of HSR. This is because among sampled long-haul routes (over 1000km), majority of them have travel time difference above 5 hours. In fact, except 2012 and 2013, more than 84% of long-haul routes are expected to experience an increase in air traffic compared with the case of no HSR competition. Meanwhile, we find that many long-haul routes have travel time difference below 5 hours. For example, the travel time difference of the Beijing-Shanghai route mentioned in the introduction is only 3.8 hours, and undoubtedly the literature finds substantial air traffic reduction in this route. Moreover, in certain years more long-haul routes will achieve over 5-hour travel time difference than the other years. For example, more than 40% ($\frac{27}{27+37}$) of the long-haul routes have travel time difference below 5 hours in 2013. This percentage is substantially larger than the other years of study. Thus, depending on the sampled routes and study period, there can be a large variety of empirical results on long-haul routes if the regression models fail to consider both the air travel time and rail travel time.

Another important observation from Table 10 is that although short-haul routes (0-500 km) overwhelmingly have travel time difference below 5 hours, this is not the case for medium-haul routes (500-1000 km). In fact, depending on the year, around 33-58% of medium-haul routes have travel time difference over 5 hours. That is, although in general most medium-haul routes are supposed to experience a reduction in air traffic, a substantial number of them may experience an increase in air traffic. This is consistent with the literature that finds negative but milder impact of

[9] Although Chen et al. (2019) did not discover that air passenger number may increase in cases with very long travel time difference, we conducted extra calculation based on their estimations and did find such cases assuming variable Hub = 0 and variable West = 0.

HSR on medium-haul routes than short-haul routes. However, since the number of medium-haul routes with over 5-hour travel time difference is substantial, it is incautious to conclude that entry of HSR reduces air traffic in medium-haul markets.

In terms of the catchment expansion effect, in general, all the models in Tables 7, 8 and 9 produce a positive coefficient of the interactive term FeedPop×AirTime with the magnitude diminishing in the threshold of feeding city distance (except the threshold of 1 hour). This coefficient becomes statistically insignificant once the threshold of feeding city distance reaches 2 hours in the main model and 2.5 hours in Eq.(M3) estimated with the sub-sample. The positive coefficients suggest that when the air leg takes a longer time, the nearby cities which can be reached by a short HSR ride will be more likely to feed extra traffic to the air leg. That is, if passengers' destinations are farther away from their origins, HSR will be more effective in feeding traffic to air transport. The catchment expansion effect seems to be the strongest when the in-vehicle time of the feeding HSR is within 0.5 hours, followed by 1.5 hours.

As the coefficient of FeedPop×AirTime estimated in Eq.(M3) is measurably larger with the full sample than that with the sub-sample, we are confident to say that the positive impacts on routes with parallel HSR entry are not entirely contributed by the catchment expansion effect. In other words, part of the positive relationship captured by FeedPop×AirTime in Eq.(M3) with the full sample comes from the air-rail competition effect due to the omission of HSR×Tdiff_m from the model. On the other hand, Eq.(M1) produces lower coefficient of FeedPop×AirTime than Eq.(M3) with the sub-sample. This might be the clue for the correlation of HSR's parallel and serial entries (co-occurrence of air-HSR competition and catchment expansion), causing part of the catchment expansion effect being captured by HSR×Tdiff_m in the main model.

The estimations of Eq.(M3) based on the sample of international routes are presented in Tables 11 and 12. As expected, catchment expansion by HSR seems to raise Chinese airlines' available seats, but not foreign airlines. Moreover, even for Chinese airlines, the available seats are only sensitive to nearby cities which can be reached within a 1-hour HSR ride. International routes of foreign airlines, however, may experience traffic reduction despite that such reduction becomes milder as the HSR feeding time increases. The reduction in foreign airlines' available seats may be explained by the reduction of short / medium – haul domestic flights (due to HSR competition) which connect passengers from gateways to other domestic destinations. Such reduction also affects Chinese airlines. However, since Chinese airlines are more attractive for

Chinese passengers and these passengers are more capable of dealing with air-HSR connection than foreign passengers, the catchment expansion effect outweighs the negative impacts of reduced connecting flights, leading to a net increase in their seat capacity. Overall, the feeding effect on international routes seems to be weaker than expected, as the domestic routes seem to enjoy stronger feeding effects. This result is implicitly consistent with Liu et al. (2019) who found that although HSR services tend to positively associate with airports' international traffic in both China and Japan, the impact is much stronger in Japan than in China.

[Insert Tables 11 and 12 here.]

6. Concluding remarks

The paper provides a possible theoretical and empirical explanation on the mixed findings about the impact of HSR entry on air traffic. In the first half of the paper, we use a model of differentiated price competition to provide a possible explanation on air traffic increase after the entry of HSR in certain long-haul markets observed by the literature. In particular, we find that in addition to extra traffic from the expanded catchment fed by HSR to the airline, the competition between these two modes may substantially drive down the airfare and hence lead to an increase in air traffic. However, such air traffic increase only happens when the air mode is in general more competitive than HSR. That is, the air travel time needs to be sufficiently shorter than the HSR travel time. Otherwise, lowering airfare cannot effectively raise air traffic.

Based on the above theoretical findings, we use a sample of Chinese air routes to empirically verify the relationship between available airline seats and rail-air travel time difference after controlling for certain catchment expansion effect of HSR. The empirical findings are consistent with the theoretical predictions. In particular, we find that competition between HSR and air mode on the same route can increase air traffic if the HSR travel time is over 5 hours longer than the air travel time, and the larger the travel time difference, the larger the air traffic increase. Otherwise, such competition tends to reduce air traffic. Meanwhile, we also observe significant air traffic increase contributed by HSR's feeding traffic to the air route from nearby cities, and such feeding effect becomes stronger as the travel time of the air leg increases. The feeding effect seems to be strongest when the HSR feeding distance is below 1.5 hours in domestic markets. However, in the international markets, the threshold is below 1 hour for Chinese airlines, but the foreign airlines' traffic is not benefited from HSR feeding.

One important policy implication of the above findings is that policy makers should be cautious if they expect the competition between HSR and air transport to cut air traffic and reduce emissions. This is especially the case when the HSR network is extensive and hence has a high potential of providing long HSR rides, e.g. in China and the European Continent. Based on our sample of Chinese domestic air routes, we find that a large share (sometimes more than half) of the air routes tend to have an increase in air traffic after the entry of HSR. These routes are not necessarily over 1000 km in air distance. Rather, many medium-haul (500-1000 km) routes may also experience post-entry air traffic increase. Air routes below 500 km, on the other hand, are almost impossible to see an increase in air traffic post-entry. That is, introducing HSR services in route markets below 500 km may effectively reduce airlines' emissions, but HSR may induce more emissions from the airlines if the air distance is more than 500 km. In the latter cases, policy makers should consider these two modes' travel time difference (instead of just the air or rail distance) when making decisions on introducing new HSR services. This implication echoes the view of Li et al. (2019a) who find that the provision of HSR service in China induced more travels and economic activities, leading to more carbon emissions.

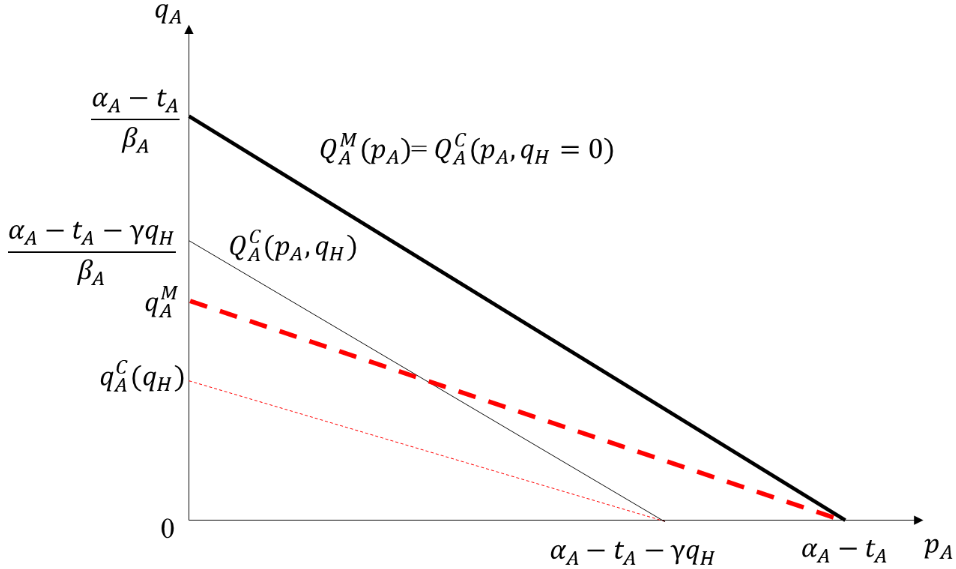
Note that the airlines' market power *before* HSR's entry, together with their market power reduction *after* HSR's entry, can be one major driving force of air traffic increase.[10] If the pre-entry air fares are already close to the marginal cost, i.e. low airline market power ex ante, it would be difficult for airlines to further reduce prices and increase traffic ex post. Of course, the complementary effect due to catchment expansion may still hold but the chance of raising airline traffic above the pre-entry level is much lower. One immediate implication of this notion is that policy makers should take into account the potential trade-off between consumer surplus and emission in the market where air transport has obvious advantage over HSR. That is, in these markets, even though air-rail competition may increase air traffic after the entry of HSR and hence increase emissions, this outcome could be welfare-enhancing if the gain in consumer surplus due to reduced market power of airlines outweighs the increment emissions. In the case of China, the airline industry is dominated by the "Big three" state-owned airlines. Although Chinese airlines do

[10] Empirically, we do not test the change in airlines' market power after the entry of HSR, as we do not have airlines' price and cost data to conduct such tests. Yet, our theoretical prediction indicates that airlines' market power is decreased after HSR entry, since the air traffic increase is induced by air fare reduction, an indicator of market power reduction when costs are unchanged.

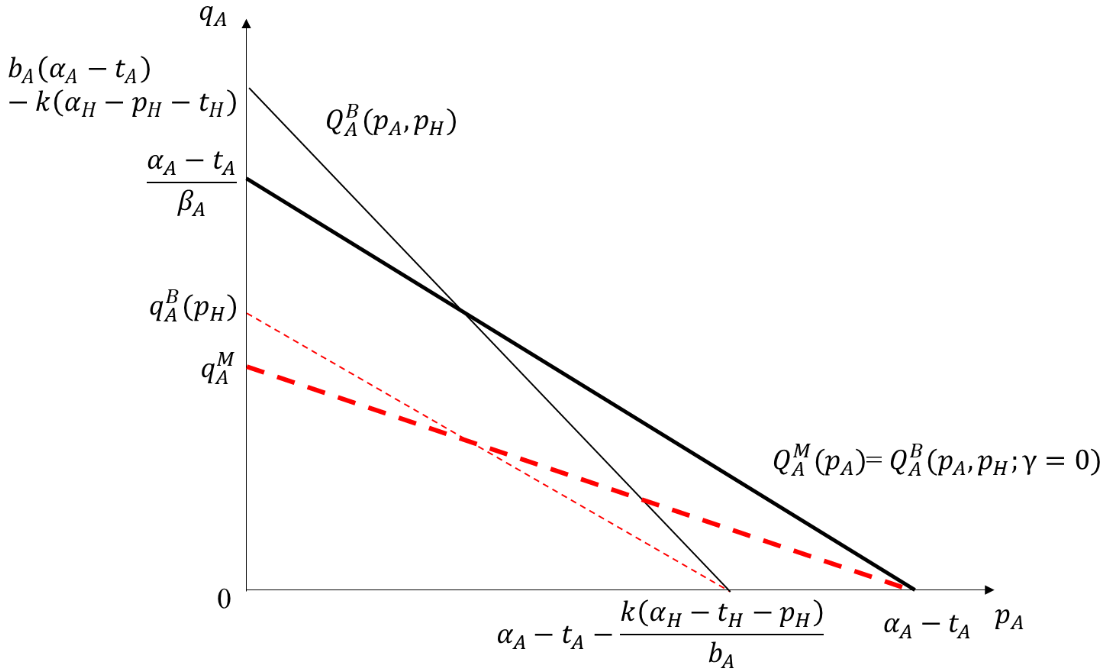
compete, they undoubtedly possess certain market power according to the Lerner index estimated by Zhang et al. (2014). Zhang et al. (2014) also found that HSR significantly reduces Chinese airlines' market power. This may partially explain our strong positive relationship between air traffic and HSR entry on routes with more than 5 hours travel time difference. This positive relationship, however, may vanish in more liberalized air transport markets, such as Europe. This result also has implications for markets where HSR services do not exist while HSR-air travel time difference could be potentially over 5 hours if HSR were introduced (most likely on long-haul routes). In these markets, airlines are likely to possess too much market power. As a result, if HSR services are not planned in these markets, policy makers may consider promoting other competitors, such as low-cost carriers which may also emit less than traditional airlines on the per passenger basis due to higher seating density, to encourage competition and improve consumer surplus.

As mentioned in Section 3, the limitation of this study mainly comes from unavailability of traffic data of non-stop, intermodal and air-air connecting routings as well as price data. As a result, we are not able to perfectly decompose substitution and complementary effects of HSR and test the mechanism of such effects. Our results also point out a few avenues for future study. First, it is worthwhile to revisit the issue of airlines' market conduct with more recent data, noting that the assumption of quantity competition may fail to generate important findings. The estimation based on a dataset of Chicago-based airlines in 1985 suggests that airlines' behaviors are close to Cournot competition (Brander and Zhang, 1990). Since then Cournot competition has been widely assumed when modeling analytically airline competition as well as air-rail competition. However, nowadays airlines are far more flexible in adjusting their fleet and schedules and revised schedules can be easily communicated via the internet, price competition may be more common now. Despite that several studies have questioned this assumption based on data from Spain and the US, we are not aware of any recent study based on the data of Chinese market. Second, empirically, it would be of value to test our idea with data from other regions, e.g. Europe. If the estimation is based on air distance, an increase in air traffic after HSR's entry is not likely to be observed in Europe, since the number of long-haul air routes with parallel HSR services is very limited in Europe. However, new results could arise if the estimation is based on rail-air travel time difference, as HSR entries on air routes between 500 km and 1000 km are not rare in Europe. Third, due to the lack of price data and realized traffic data, our empirical part can only estimate the net impact of HSR entry on airlines' seat capacity. If the relevant data become available in the future, we will be able to estimate a demand or structural model that incorporates flight frequency and price, the other two major determinants of travel demand. In this way, we can test the mechanism behind the seat capacity change and verify whether price reduction is the driving force of seat capacity increase in markets with more than 5 hours travel time difference.

Figures



(a) Airline's perceived demand functions: Cournot vs. monopoly



(b) Airline's perceived demand functions: Bertrand vs. monopoly

Figure 1 Illustration of the difference of Counrot and Bertrand outcomes

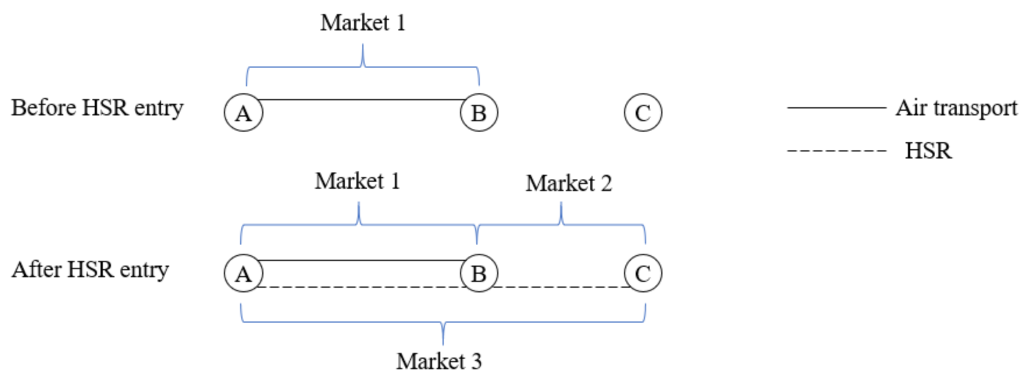


Figure 2 Three-city network: Before vs. after HSR entry

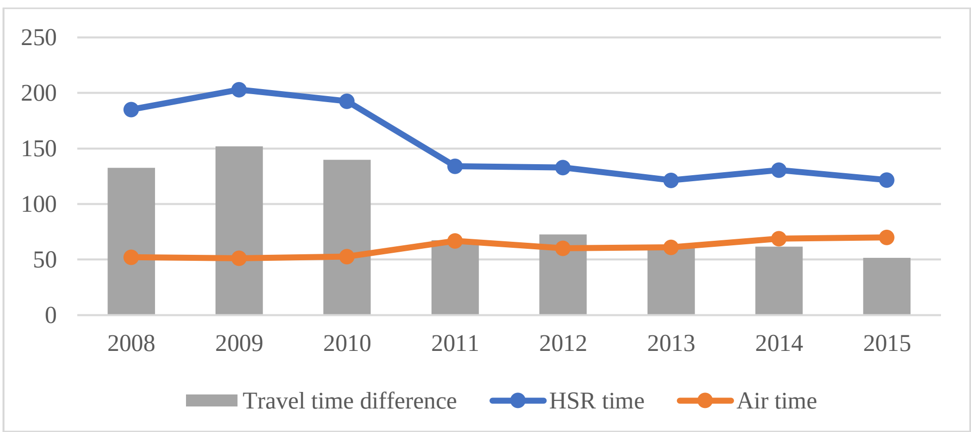


Figure 3 Scheduled in-vehicle times of Beijing-Jinan route across time

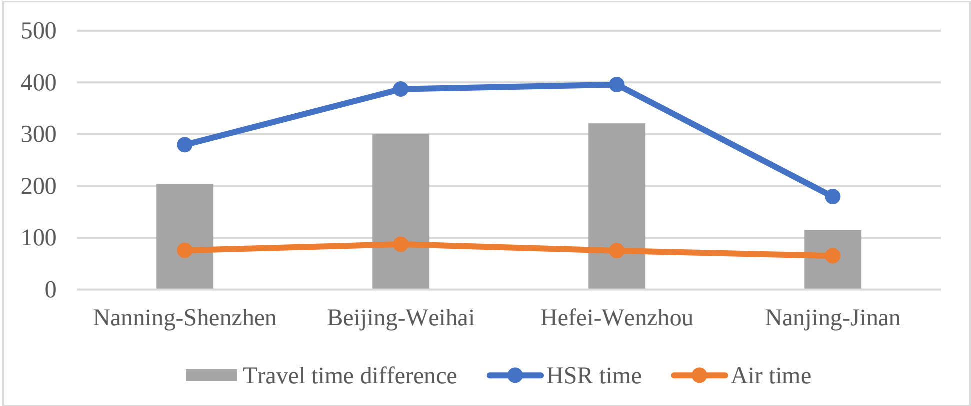


Figure 4 Scheduled in-vehicle times of routes with similar air distance (580km) in 2015

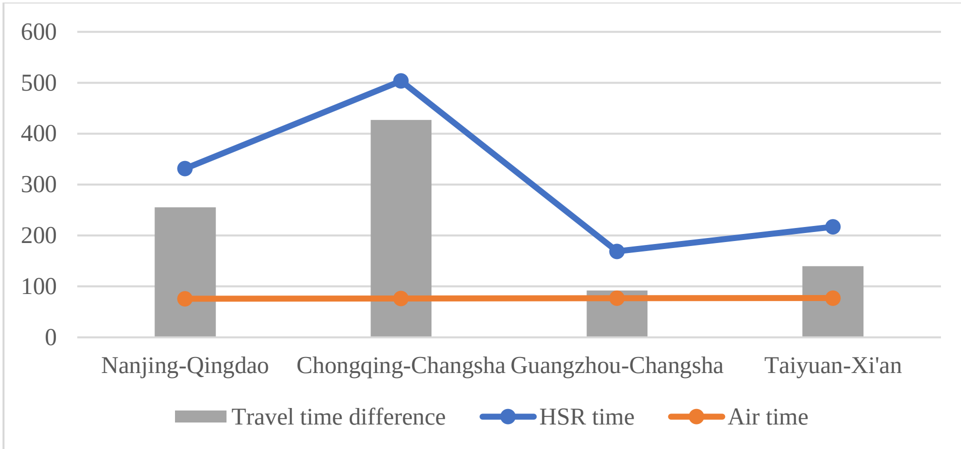


Figure 5 Scheduled in-vehicle times of routes with similar air travel time (76 min) in 2015

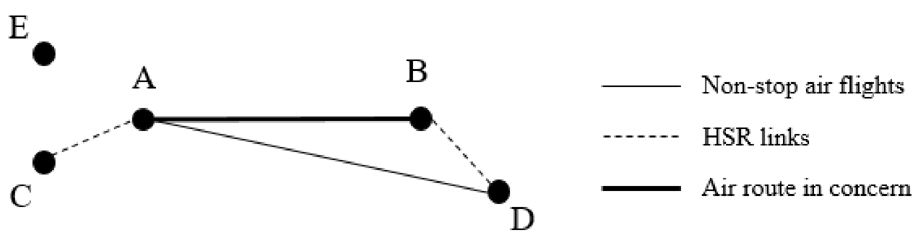


Figure 6 Illustration of feeding cities of air route AB

Tables

Table 1 Impacts of raising t_{1A}, t_{1H}, t_{2H} and w on air fare and air traffic

Impact of factor x	$x = t_{1A}$	$x = t_{1H}$	$x = t_{2H}$	$x = w$
$\frac{dp_{1A}^B}{dx}$	-	+	- iff $\gamma < \beta_H$	-
$\frac{dq_{1A}^B}{dx}$	-	+	+ iff $\gamma < \beta_H$	+
$\frac{dq_{3A}^B}{dx}$	-	+	- iff $\gamma < \beta_H$	-
$\frac{dQ_A^B}{dx}$	-	+	- iff $\gamma < \beta_H$	-
$\frac{d(p_{1A}^B - p_{1A}^M)}{dx}$	+	+	- iff $\gamma < \beta_H$	-
$\frac{d(q_{1A}^B - q_{1A}^M)}{dx}$	-	+	+ iff $\gamma < \beta_H$	+
$\frac{d(Q_A^B - Q_A^M)}{dx}$	-	+	- iff $\gamma < \beta_H$	-

Table 2 Operation years of air routes

Years of airline operation	**Domestic routes**	**International routes**
4	193	69
5	148	83
6	172	47
7	193	65
8	1,530	267
Total	2,236	531

Source: Summarized by the authors based on OAG Schedule database.

Table 3 Number of air routes with the presence of parallel HSR services

Year	No. of routes
2008	58
2009	120
2010	145
2011	189
2012	163
2013	245
2014	481
2015	713

Source: Summarized by the authors based on National Rail Timetable of China July editions.

Table 4 Nine categories of travel time difference (Tdiff_1 ~ Tdiff_9)

Dummy variable	Range of rail-air travel time difference	Obs	Air route distances (km)			
			Mean	Std. Dev.	Min	Max
Tdiff_1	Below 2 hours	151	432.4	139.8	219	661
Tdiff_2	2-3 hours	290	565.1	187.5	259	948
Tdiff_3	3-4 hours	318	660.0	238.1	259	1,147
Tdiff_4	4-5 hours	316	742.3	264.8	327	1,659
Tdiff_5	5-6 hours	274	901.0	278.0	327	1,879
Tdiff_6	6-7 hours	257	997.1	302.5	441.1	1,953
Tdiff_7	7-8 hours	176	1,121	330.3	467	1,953
Tdiff_8	8-9 hours	125	1,177	312.7	576.5	1,886
Tdiff_9	Above 9 hours	207	1,333	246.1	576.5	2,095
	No HSR presence	15,774	1,082	556.0	154	4,053
	Total	17,888	1,054.26	542.47	154	4,053

Note: The number of routes in each group is not shown because a route can be categorized into different groups as travel time changes over time.

Table 5 Variable notations and definitions

Variable notation	Definition
$Seat_{it}$	Total available air seats on route i in year t
$AirTime_{it}$	Arithmetic mean of air in-vehicle time on route i in year t
HSR_{it}	Dummy variable. It takes a value of 1 if there exists direct HSR service in route i in year t; otherwise, it takes a value of 0.
$Tdiff\_1_{it}$ ~ $Tdiff\_9_{it}$	A set of nine dummy variables indicating the travel time difference between HSR's average in-vehicle time and air mode's average in-vehicle time on route i in year t. Each dummy variable representing one range of travel time difference.
$HSRFreq_{it}$	Average daily HSR frequency on route i in year t
$FeedPop_{it}$	Total population of the effective HSR feeding cities of route i in year t
$RoutePop_{it}$	Total population of the two endpoint cities of route i in year t
$RouteGDP_{it}$	The sum of GDP per capita of the two endpoint cities of route i in year t

Table 6 Descriptive statistics of non-dummy variables (domestic routes)

Variable	Obs	Mean	Std. Dev.	Min	Max
Seat	17,888	159,830	295,175	0	4,671,000
HSRTime (minutes)	2,114	418.1	182.4	45.25	959
AirTime (minutes)	17,888	114.1	45.75	25	392
HSRFreq	17,888	1.883	10.45	0	218
FeedPop0.5h ('000)	17,888	2,256	3,846	0	31,277
FeedPop1h ('000)	17,888	13,356	13,943	0	92,484
FeedPop1.5h ('000)	17,888	24,198	21,844	0	125,398
FeedPop2h ('000)	17,888	33,507	29,586	0	185,132
FeedPop2.5h ('000)	17,888	44,690	38,149	0	218,124
FeedPop3h ('000)	17,888	54,038	46,172	0	257,665
RoutePop ('000)	17,888	119,770	48,139	8,301	322,606
RouteGDP ('000)	17,888	16,826	8,284	1,199	60,331

Note: The thresholds used to identify effective HSR feeding cities are shown after "FeedPop". Specifically, "FeedPop0.5h" refers to the total population of feeding cities that can reach the nearest endpoint cities within 0.5 hours by a direct HSR ride. HSRTime indicates the average HSR in-vehicle time. Although this variable is not directly used in the regression, it is used to calculate travel time difference.

Table 7 Regression results of domestic routes (feeding threshold: 0.5 and 1 hours)

Feeding city threshold		0.5 hours			1 hour		
Variables	Eq.(M2) Full sample	Eq.(M1) Full sample	Eq.(M3) Full sample	Eq.(M3) Sub-sample	Eq.(M1) Full sample	Eq.(M3) Full sample	Eq.(M3) Sub-sample
HSR×Tdiff_m							
Below 2 hours	-97,267***	-99,774***			-97,739***		
(m = 1)	(7,572)	(7,556)			(7,580)		
2-3 hours	-84,846***	-85,772***			-84,985***		
(m = 2)	(5,479)	(5,465)			(5,480)		
3-4 hours	-22,096***	-22,104***			-22,280***		
(m = 3)	(4,650)	(4,637)			(4,652)		
4-5 hours	-10,074**	-10,855**			-10,342**		
(m = 4)	(4,300)	(4,289)			(4,305)		
5-6 hours	18,634***	18,345***			18,306***		
(m = 5)	(4,334)	(4,322)			(4,341)		
6-7 hours	38,464***	37,126***			38,273***		
(m = 6)	(4,253)	(4,244)			(4,255)		
7-8 hours	42,947***	41,177***			42,629***		
(m = 7)	(4,903)	(4,893)			(4,908)		
8-9 hours	49,246***	48,378***			49,141***		
(m = 8)	(5,619)	(5,604)			(5,619)		
Above 9 hours	62,854***	61,774***			62,815***		
(m = 9)	(4,485)	(4,474)			(4,485)		
HSR×HSRFreq	-989.0***	-948.6***			-981.0***		
	(82.26)	(82.15)			(82.47)		
FeedPop×AirTime		0.0138***	0.0162***	0.0123***	0.000744	0.00177***	0.000979*
		(0.00148)	(0.00154)	(0.00145)	(0.000553)	(0.000575)	(0.000541)
RouteGDP	0.118**	-0.0150	-0.0300	-0.126***	0.102**	0.0876*	-0.0407
	(0.0486)	(0.0505)	(0.0522)	(0.0481)	(0.0501)	(0.0518)	(0.0480)
RoutePop	21.10***	20.03***	17.74***	10.84***	20.82***	18.30***	11.52***
	(0.838)	(0.844)	(0.872)	(0.902)	(0.863)	(0.893)	(0.922)
Constant	-232,687***	-205,747***	-169,110***	-84,743***	-227,516***	-187,994***	-101,285***
	(13,229)	(13,503)	(13,882)	(13,118)	(13,775)	(14,173)	(13,392)
Route FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.343	0.347	0.286	0.350	0.343	0.281	0.346
Number of routes	2,236	2,236	2,236	1,509	2,236	2,236	1,509
Observations	17,888	17,888	17,888	12,072	17,888	17,888	12,072

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 8 Regression results of domestic routes (feeding threshold: 1.5 and 2 hours)

Feeding city threshold	1.5 hours			2 hours		
Variables	Eq. (M1) Full sample	Eq.(M3) Full sample	Eq.(M3) Sub-sample	Eq.(M1) Full sample	Eq.(M3) Full sample	Eq.(M3) Sub-sample
HSR×Tdiff_m						
Below 2 hours	-98,241***			-97,807***		
(m = 1)	(7,579)			(7,580)		
2-3 hours	-85,434***			-85,249***		
(m = 2)	(5,482)			(5,485)		
3-4 hours	-22,553***			-22,468***		
(m = 3)	(4,652)			(4,656)		
4-5 hours	-10,732**			-10,642**		
(m = 4)	(4,306)			(4,316)		
5-6 hours	17,932***			18,094***		
(m = 5)	(4,341)			(4,348)		
6-7 hours	37,961***			38,080***		
(m = 6)	(4,256)			(4,260)		
7-8 hours	42,167***			42,339***		
(m = 7)	(4,910)			(4,918)		
8-9 hours	48,701***			48,781***		
(m = 8)	(5,621)			(5,627)		
Above 9 hours	62,282***			62,519***		
(m = 9)	(4,489)			(4,490)		
HSR×HSRFreq	-974.9***			-981.4***		
	(82.41)			(82.41)		
FeedPop×AirTime	0.00121***	0.00205***	0.00176***	0.000504	0.00118***	0.000953***
	(0.000444)	(0.000461)	(0.000435)	(0.000326)	(0.000338)	(0.000319)
RouteGDP	0.0855*	0.0701	-0.0637	0.0971*	0.0756	-0.0556
	(0.0500)	(0.0518)	(0.0478)	(0.0505)	(0.0523)	(0.0481)
RoutePop	20.47***	17.89***	10.95***	20.81***	18.26***	11.31***
	(0.869)	(0.899)	(0.927)	(0.859)	(0.889)	(0.919)
Constant	-222,004***	-181,921***	-92,948***	-227,377***	-187,382***	-98,004***
	(13,791)	(14,211)	(13,390)	(13,669)	(14,095)	(13,293)
Route FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.344	0.282	0.347	0.343	0.281	0.346
Number of routes	2,236	2,236	1,509	2,236	2,236	1,509
Observations	17,888	17,888	12,072	17,888	17,888	12,072

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 9 Regression results of domestic routes (feeding threshold: 2.5 and 3 hours)

Feeding city threshold	2.5 hours			3 hours		
Variables	Eq. (M1) Full sample	Eq.(M3) Full sample	Eq.(M3) Sub-sample	Eq.(M1) Full sample	Eq.(M3) Full sample	Eq.(M3) Sub-sample
HSR×Tdiff_m						
Below 2 hours	-97,350***			-96,887***		
(m = 1)	(7,579)			(7,579)		
2-3 hours	-84,892***			-84,653***		
(m = 2)	(5,482)			(5,481)		
3-4 hours	-22,168***			-21,788***		
(m = 3)	(4,659)			(4,658)		
4-5 hours	-10,179**			-9,544**		
(m = 4)	(4,320)			(4,325)		
5-6 hours	18,518***			19,247***		
(m = 5)	(4,357)			(4,367)		
6-7 hours	38,390***			38,907***		
(m = 6)	(4,262)			(4,270)		
7-8 hours	42,824***			43,567***		
(m = 7)	(4,926)			(4,932)		
8-9 hours	49,168***			49,648***		
(m = 8)	(5,627)			(5,630)		
Above 9 hours	62,790***			63,171***		
(m = 9)	(4,492)			(4,493)		
HSR×HSRFreq	-987.4***			-996.5***		
	(82.49)			(82.52)		
FeedPop×AirTime	0.0000687	0.000942***	0.000470*	-0.000250	0.000627***	0.000240
	(0.000266)	(0.000274)	(0.000260)	(0.000218)	(0.000223)	(0.000212)
RouteGDP	0.115**	0.0766	-0.0410	0.136***	0.0798	-0.0355
	(0.0504)	(0.0523)	(0.0480)	(0.0510)	(0.0530)	(0.0486)
RoutePop	21.04***	18.23***	11.53***	21.28***	18.48***	11.72***
	(0.862)	(0.892)	(0.922)	(0.854)	(0.883)	(0.913)
Constant	-231,757***	-187,103***	-101,769***	-236,328***	-190,750***	-104,493***
	(13,709)	(14,127)	(13,320)	(13,605)	(14,018)	(13,234)
Route FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.343	0.281	0.346	0.343	0.281	0.346
Number of routes	2,236	2,236	1,509	2,236	2,236	1,509
Observations	17,888	17,888	12,072	17,888	17,888	12,072

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 10 Number of air routes by air distance and travel time difference for each year

Air route distance		0-500 km		500-1000 km		Over 1000 km		All distances
Travel time difference		less than 5 hours	more than 5 hours	less than 5 hours	more than 5 hours	less than 5 hours	more than 5 hours	more than 5 hours
2008	N	12	0	21	21	0	4	25
	%	20.7%	0%	36.2%	36.2%	0%	6.9%	43.1%
2009	N	28	0	30	42	0	20	62
	%	23.3%	0%	25.0%	35.0%	0%	16.7%	51.6%
2010	N	36	3	41	43	0	22	68
	%	24.8%	2.1%	28.3%	29.7%	0%	15.2%	46.9%
2011	N	37	2	58	32	8	52	86
	%	19.6%	1.1%	30.7%	16.9%	4.2%	27.5%	45.5%
2012	N	37	2	57	39	7	21	62
	%	22.7%	1.2%	35%	23.9%	4.3%	12.9%	38.0%
2013	N	39	2	94	46	27	37	85
	%	15.9%	0.8%	38.4%	18.8%	11.0%	15.1%	34.6%
2014	N	67	2	114	108	30	160	270
	%	13.9%	0.4%	23.7%	22.5%	6.2%	33.3%	56.1%
2015	N	110	1	187	115	35	265	381
	%	15.4%	0.1%	26.2%	16.1%	4.9%	37.2%	53.4%

Note: Each cell in row "N" shows the number of routes in the corresponding distance and travel-time difference category. Each cell in row "%" shows the percentage of such routes among all sampled air routes with parallel HSR services.

Table 11 Regression results of international routes (Chinese airlines)

	(1)	(2)	(3)	(4)	(5)	(6)
Feeding city threshold	0.5 hours	1 hour	1.5 hours	2 hours	2.5 hours	3 hours
Variables						
FeedPop×AirTime	0.00203**	0.000745***	0.0000852	-0.00000179	-0.0000786	0.0000723
	(0.00100)	(0.000255)	(0.000232)	(0.000194)	(0.000148)	(0.000128)
RouteGDP	0.448***	0.387***	0.497***	0.510***	0.526***	0.484***
	(0.124)	(0.127)	(0.125)	(0.126)	(0.124)	(0.128)
RoutePop	5.448***	4.965***	5.984***	6.196***	6.485***	5.935***
	(1.202)	(1.218)	(1.276)	(1.269)	(1.273)	(1.232)
Constant	-41,406***	-33,636**	-50,260***	-53,121***	-56,932***	-49,232***
	(15,247)	(15,598)	(16,046)	(15,987)	(15,923)	(15,662)
Route FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.185	0.186	0.184	0.183	0.184	0.184
Number of routes	350	350	350	350	350	350
Observations	2,800	2,800	2,800	2,800	2,800	2,800

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 12 Regression results of international routes (Foreign airlines)

	(1)	(2)	(3)	(4)	(5)	(6)
Feeding city threshold	0.5 hours	1 hour	1.5 hours	2 hours	2.5 hours	3 hours
Variables						
FeedPop×AirTime	-0.00104	-0.000594**	-0.000492**	-0.000376**	-0.000399***	-0.000287**
	(0.000964)	(0.000261)	(0.000220)	(0.000178)	(0.000136)	(0.000121)
RouteGDP	0.191	0.225*	0.212*	0.214*	0.227*	0.236*
	(0.127)	(0.127)	(0.125)	(0.126)	(0.125)	(0.128)
RoutePop	3.842***	4.543***	4.765***	4.601***	5.054***	4.518***
	(1.234)	(1.278)	(1.319)	(1.302)	(1.304)	(1.267)
Constant	5,465	-3,924	-5,325	-3,481	-8,847	-3,129
	(16,289)	(16,745)	(17,043)	(16,878)	(16,797)	(16,505)
Route FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	0.215	0.216	0.216	0.216	0.217	0.216
Number of routes	333	333	333	333	333	333
Observations	2,664	2,664	2,664	2,664	2,664	2,664

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Appendix A: Proof of Proposition 2

The main text has proven that $q_A^B > q_A^M$ may hold if and only if $q_A^B > \frac{\beta_A}{\gamma} q_H$. Solving for the airline's best-response function based on equation (9), we get:

$$p_A^B(p_H) = \frac{a_A - b_A t_A + k(p_H + t_H)}{2b_A}$$

Plugging the above expression into the demand functions, we have:

$$q_A^B(p_H) = \frac{\beta_H(\alpha_A - t_A) - \gamma(\alpha_H - p_H - t_H)}{2\delta} \text{ and } q_H\,(p_H) = \frac{1}{\delta}\left[\frac{(2\beta_A\beta_H - \gamma^2)(\alpha_H - p_H - t_H)}{2\beta_H} + \frac{\gamma(\alpha_A + t_A)}{2}\right]$$

Then, at any p_H, $q_A^B > \frac{\beta_A}{\gamma} q_H$ is equivalent to $\alpha_A - t_A > \frac{\beta_A \alpha_A}{\beta_A + \beta_H} + \frac{[\beta_A(2\beta_A\beta_H - \gamma^2) + \beta_H\gamma^2](\alpha_H - p_H - t_H)}{\beta_H\gamma(\beta_A + \beta_H)}$.

Alternatively, for any given q_H, the airline's quantity can be written as:

$$q_A^B(q_H) = \frac{\alpha_A - t_A - \gamma q_H}{2\beta_A - \frac{\gamma^2}{\beta_H}}$$

Then, at any q_H, $q_A^B > \frac{\beta_A}{\gamma} q_H$ is equivalent to $\alpha_A - t_A > \frac{[\beta_A(2\beta_A\beta_H - \gamma^2) + \beta_H\gamma^2]q_H}{\beta_H\gamma}$. In both cases, $q_A^B > q_A^M$ tends to hold when t_A is sufficiently small.

In terms of air fare, using equations (2), (4) and (10), we have $p_A^B - p_A^M = \beta_A q_A^M - \beta_A q_A^B - \gamma q_H = \frac{\gamma}{2} q_H - \frac{\gamma^2}{2\beta_H} q_A^B - \gamma q_H = -\frac{\gamma(\gamma\beta_A q_A^M + \delta q_H)}{\beta_A\beta_H + \delta} \leq 0$ and the equal sign holds when $\gamma = 0$.

Q.E.D.

Appendix B: Proof of Corollary 1

When both the airline and the HSR choose prices, from Proposition 2 and equation (10), the following two equations hold simultaneously:

$$\left(1 - \frac{\gamma^2}{2\beta_A\beta_H}\right) q_A^B = q_A^M - \frac{\gamma}{2\beta_A} q_H^B, \text{ where } q_A^M = \frac{\alpha_A - t_A}{2\beta_A}$$

$$\left(1 - \frac{\gamma^2}{2\beta_A\beta_H}\right) q_H^B = q_H^M - \frac{\gamma}{2\beta_H} q_A^B, \text{ where } q_H^M = \frac{\alpha_H - t_H}{2\beta_H}$$

Solving the above two equations for q_A^B and q_H^B, we obtain the equilibrium quantity for the airline:

$$q_A^B = \frac{\left(1 - \frac{\gamma^2}{2\beta_A\beta_H}\right) q_A^M - \frac{\gamma}{2\beta_A} q_H^M}{\frac{1}{4}\left(1 - \frac{\gamma^2}{\beta_A\beta_H}\right)\left(4 - \frac{\gamma^2}{\beta_A\beta_H}\right)}$$

Therefore,

$$q_A^B - q_A^M = \frac{\frac{\gamma^2}{4\beta_A\beta_H}\left(3 - \frac{\gamma^2}{\beta_A\beta_H}\right)q_A^M - \frac{\gamma}{2\beta_A}q_H^M}{\frac{1}{4}\left(1 - \frac{\gamma^2}{\beta_A\beta_H}\right)\left(4 - \frac{\gamma^2}{\beta_A\beta_H}\right)}$$

Since the denominator of the above expression is positive, $q_A^B - q_A^M > 0$ holds if and only if the numerator $\frac{\gamma^2}{4\beta_A\beta_H}\left(3 - \frac{\gamma^2}{\beta_A\beta_H}\right)q_A^M - \frac{\gamma}{2\beta_A}q_H^M > 0$. After substituting q_A^M and q_H^M, this condition is equivalent to $\frac{\alpha_A - t_A}{\alpha_H - t_H} > \frac{2\beta_A^2\beta_H}{\gamma(3\beta_A\beta_H - \gamma^2)}$.

Q.E.D.

Appendix C: Proof of Proposition 3

As demonstrated in equation (15), $q_{1A}^B > q_{1A}^M$ may hold if

(i) The first term of equation (14) is larger than q_{1A}^M. That is, the substitution effect from the original parallel market is positive, i.e. $q_{1H} < \frac{\gamma_1}{\beta_{1A}}q_{1A}^M$; and
(ii) The second term of equation (14) is positive. That is, the newly created complementary market is weak, i.e. $b_{3A}p_{1A}^B > q_{3A}^B$.

Point (ii) suggests that after controlling for the substitution effect (i), extra market from catchment expansion may reduce the traffic in the original overlapping market, if the newly added market is too strong.

From equation (16), we know $Q_A^B > Q_A^M$ may hold if the substitution effect in the original parallel market is either positive, i.e. $q_{1H} < \frac{\gamma_1}{\beta_{1A}}q_{1A}^M$, or negative but weaker than the positive complementary effect (the second term of equation (15)).

Q.E.D.

Appendix D: Proof of Corollary 2

Following Appendix C, as $p_{1A}^B = 2\beta_{1A}q_{1A}^M - \beta_{1A}q_{1A}^B - \gamma_1 q_{1H}$ and $p_{1A}^M = \beta_{1A}q_{1A}^M$, we have $p_{1A}^B - p_{1A}^M = \beta_{1A}(q_{1A}^M - q_{1A}^B) - \gamma_1 q_{1H}$. Using equation (15), we have

$$\beta_{1A}(q_{1A}^M - q_{1A}^B) = -\frac{\gamma_1(\gamma_1\beta_{1A}q_{1A}^M - \beta_{1A}\beta_{1H}q_{1H})}{\beta_{1A}\beta_{1H} + \delta_1} - \frac{\beta_{1A}\delta_1(b_{3A}p_{1A}^B - q_{3A}^B)}{\beta_{1A}\beta_{1H} + \delta_1}$$

$$p_{1A}^B - p_{1A}^M = -\frac{\gamma_1(\gamma_1\beta_{1A}q_{1A}^M + \delta_1 q_{1H})}{\beta_{1A}\beta_{1H} + \delta_1} - \frac{\beta_{1A}\delta_1(b_{3A}p_{1A}^B - q_{3A}^B)}{\beta_{1A}\beta_{1H} + \delta_1}$$

Since the second term can be positive when $b_{3A}p_{1A}^B < q_{3A}^B$, $p_{1A}^B > p_{1A}^M$ may occur. That is, if the complementary market is strong enough relative to the original overlapping market, air fare may increase after the entry of HSR. Alternatively, as long as the complementary market is weak, air fare will reduce after the entry of HSR. Moreover, as $-\beta_{1A}\beta_{1H}q_H < \delta_1 q_H$, the above two equations imply that $p_{1A}^B - p_{1A}^M < \beta_{1A}(q_{1A}^M - q_{1A}^B)$ always holds. That is, $p_{1A}^B - p_{1A}^M > 0$ implies $q_{1A}^M - q_{1A}^B > 0$; and $q_{1A}^M - q_{1A}^B < 0$ implies $p_{1A}^B - p_{1A}^M < 0$.

Q.E.D.

Appendix E: Proof of results in Table 1 and Proposition 4

After imposing the assumption that $\beta_{mi} = \beta_i$, $\gamma_m = \gamma$, $b_{mi} = b_i$, $k_m = k$ and $\delta_m = \delta$, the airline's first-order condition (FOC) is:

$$\frac{\partial \pi_A}{\partial p_{1A}} = q_{1A} + q_{3A} - 2b_A p_{1A} = 0$$

The HSR's FOC's are:

$$\frac{\partial \pi_H}{\partial p_{1H}} = q_{1H} - b_H p_{1H} = 0$$

$$\frac{\partial \pi_H}{\partial p_{2H}} = q_{2H} + q_{3A} + \left(-\frac{1}{\beta_H} - b_A\right) p_{2H} + k p_{3H} = 0$$

$$\frac{\partial \pi_H}{\partial p_{3H}} = q_{3H} - b_H p_{3H} + \mathrm{k} p_{2H} = 0$$

Take derivative on both sides of the above FOC's with respect to each factor *x*:

$$-4\beta_H \frac{dp_{1A}^B}{dx} + \gamma \frac{dp_{1H}^B}{dx} - \beta_H \frac{dp_{2H}^B}{dx} + \gamma \frac{dp_{3H}^B}{dx} + \delta \frac{\partial q_{1A}}{\partial x} + \delta \frac{\partial q_{3A}}{\partial x} = 0 \qquad \text{(D1)}$$

$$\gamma \frac{dp_{1A}^B}{dx} - 2\beta_A \frac{dp_{1H}^B}{dx} + \delta \frac{\partial q_{1H}}{\partial x} = 0 \qquad \text{(D2)}$$

$$-\beta_H \frac{dp_{1A}^B}{dx} - 2(\frac{\delta}{\beta_H} + \beta_H) \frac{dp_{2H}^B}{dx} + 2\gamma \frac{dp_{3H}^B}{dx} + \delta \frac{\partial q_{2H}}{\partial x} + \delta \frac{\partial q_{3A}}{\partial x} = 0 \qquad \text{(D3)}$$

$$\gamma \frac{dp_{1A}^B}{dx} + 2\gamma \frac{dp_{2H}^B}{dx} - 2\beta_A \frac{dp_{3H}^B}{dx} + \delta \frac{\partial q_{3H}}{\partial x} = 0 \qquad \text{(D4)}$$

Solve the equation system (D1) ~ (D4) for $\frac{dp_{1A}^B}{dx}$, $\frac{dp_{1H}^B}{dx}$, $\frac{dp_{2H}^B}{dx}$ and $\frac{dp_{3H}^B}{dx}$, and substitute the results into $\frac{dq_{1A}^B}{dx} = \frac{\partial q_{1A}}{\partial p_{1A}}\frac{dp_{1A}^B}{dx} + \frac{\partial q_{1A}}{\partial p_{1H}}\frac{dp_{1H}^B}{dx} + \frac{\partial q_{1A}}{\partial x}$ and $\frac{dq_{3A}^B}{dx} = \frac{\partial q_{3A}}{\partial p_{1A}}\frac{dp_{1A}^B}{dx} + \frac{\partial q_{3A}}{\partial p_{2H}}\frac{dp_{2H}^B}{dx} + \frac{\partial q_{3A}}{\partial p_{3H}}\frac{dp_{3H}^B}{dx} + \frac{\partial q_{3A}}{\partial x}$. In particular, when $x = t_{1A}$, we can obtain the following:

$\frac{dp_{1A}^B}{dt_{1A}} = -\frac{\beta_A\beta_H(3\beta_H+4\beta_A)-\gamma^2(\beta_H+2\beta_A)}{\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A)} < 0,$

$\frac{dq_{1A}^B}{dt_{1A}} = \frac{-2\beta_H(\beta_H+\beta_A)(2\beta_A\beta_H-\gamma^2)}{\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} < 0,$

$$\frac{dq_{3A}^B}{dt_{1A}} = \frac{-2\beta_A\beta_H(\beta_H{}^2+2\beta_A\beta_H-\gamma^2)}{\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} < 0,$$

$$\frac{dQ_A^B}{dt_{1A}} = \frac{dq_{1A}^B}{dt_{1A}} + \frac{dq_{3A}^B}{dt_{1A}} = \frac{2\beta_H}{\delta}\frac{dp_{1A}^B}{dt_{1A}} < 0$$

Since $\frac{dp_A^M}{dt_{1A}} = -\frac{1}{2}$ and $\frac{dq_{1A}^M}{dt_{1A}} = \frac{dQ_A^M}{dt_{1A}} = \frac{-1}{2\beta_A}$, we have:

$$\frac{d(p_{1A}^B-p_A^M)}{dt_{1A}} = \frac{dp_{1A}^B}{dt_{1A}} + \frac{1}{2} = \frac{\beta_A\beta_H{}^2+\gamma^2(\beta_H+2\beta_A)}{\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A)} > 0,$$

$$\frac{d(q_{1A}^B-q_{1A}^M)}{dt_{1A}} = \frac{dq_{1A}^B}{dt_{1A}} + \frac{1}{2\beta_A} = \frac{-\beta_A{}^2\beta_H{}^3-\gamma^2[\beta_A\beta_H(4\beta_H+6\beta_A)-\gamma^2(\beta_H+2\beta_A)]}{2\beta_A\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} < 0,$$

$$\frac{d(Q_A^B-Q_A^M)}{dt_{1A}} = \frac{dQ_A^B}{dt_{1A}} + \frac{1}{2\beta_A} = \frac{-\beta_A{}^2\beta_H{}^2(5\beta_H+8\beta_A)-\gamma^2[\beta_A\beta_H(4\beta_H+2\beta_A)-\gamma^2(\beta_H+2\beta_A)]}{2\beta_A\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} < 0.$$

When $x = t_{1H}$, we can then obtain the following:

$$\frac{dp_{1A}^B}{dt_{1H}} = \frac{d(p_{1A}^B-p_A^M)}{dt_{1H}} = \frac{2\gamma\beta_A(\beta_H+\beta_A)}{\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A)} > 0,$$

$$\frac{dq_{1A}^B}{dt_{1H}} = \frac{d(q_{1A}^B-q_{1A}^M)}{dt_{1H}} = \frac{\beta_H\gamma(3\beta_H\beta_A+4\beta_A{}^2+\gamma^2)}{2\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} > 0,$$

$$\frac{dq_{3A}^B}{dt_{1H}} = \frac{\beta_H\gamma(5\beta_H\beta_A+4\beta_A{}^2-\gamma^2)}{2\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} > 0, \frac{dQ_A^B}{dt_{1H}} = \frac{d(Q_A^B-Q_A^M)}{dt_{1H}} = \frac{dq_{1A}^B}{dt_{1H}} + \frac{dq_{3A}^B}{dt_{1H}} = \frac{2\beta_H}{\delta}\frac{\partial p_{1A}^B}{\partial t_{1H}} > 0.$$

When $x = t_{2H}$, we can then obtain the following:

$$\frac{dp_{1A}^B}{dt_{2H}} = \frac{d(p_{1A}^B-p_A^M)}{dt_{2H}} = \frac{\beta_A(\beta_H+\beta_A)(\gamma-\beta_H)}{\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A)} < 0 \text{ iff } \gamma < \beta_H$$

$$\frac{dq_{1A}^B}{dt_{2H}} = \frac{d(q_{1A}^B-q_{1A}^M)}{dt_{2H}} = \frac{-(\beta_H+\beta_A)(\gamma-\beta_H)(2\beta_A\beta_H-\gamma^2)}{2\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} > 0 \text{ iff } \gamma < \beta_H$$

$$\frac{dq_{3A}^B}{dt_{2H}} = \frac{(\beta_H+\beta_A)(\gamma-\beta_H)(6\beta_A\beta_H-\gamma^2)}{2\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} < 0 \text{ iff } \gamma < \beta_H$$

$$\frac{dQ_A^B}{dt_{2H}} = \frac{d(Q_A^B-Q_A^M)}{dt_{2H}} = \frac{dq_{1A}^B}{dt_{2H}} + \frac{dq_{3A}^B}{dt_{2H}} = \frac{2\beta_H}{\delta}\frac{dp_{1A}^B}{dt_{2H}} < 0 \text{ iff } \gamma < \beta_H$$

When $x = w$, we can then obtain the following:

$$\frac{dp_{1A}^B}{dw} = \frac{d(p_{1A}^B-p_A^M)}{dw} = \frac{-\beta_A(\beta_H{}^2+2\beta_A\beta_H-\gamma^2)}{\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A)} < 0,$$

$$\frac{dq_{1A}^B}{dw} = \frac{d(q_{1A}^B-q_{1A}^M)}{dw} = \frac{(\beta_H{}^2+2\beta_A\beta_H-\gamma^2)(2\beta_A\beta_H-\gamma^2)}{2\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} > 0,$$

$$\frac{dq_{3A}^B}{dw} = \frac{-(\beta_H{}^2+2\beta_A\beta_H-\gamma^2)(6\beta_A\beta_H-\gamma^2)}{2\delta(\beta_A\beta_H(7\beta_H+8\beta_A)-\gamma^2(\beta_H+2\beta_A))} < 0,$$

$\frac{dQ_A^B}{dw} = \frac{d(Q_A^B - Q_A^M)}{dw} = \frac{dq_{1A}^B}{dw} + \frac{dq_{3A}^B}{dw} = \frac{2\beta_H}{\delta}\frac{\partial p_{1A}^B}{\partial w} < 0.$

As $\frac{dq_{1A}^B}{dx}$ and $\frac{dq_{3A}^B}{dx}$ are both independent of each factor *x*, all equilibrium quantities are linear in each factor *x*. Therefore, we can write equilibrium air traffic in various markets into the following:

$$q_{1A}^B = C_{1A} + \frac{dq_{1A}^B}{dt_{1A}} t_{1A} + \frac{dq_{1A}^B}{dt_{1H}} t_{1H} + \frac{dq_{1A}^B}{dt_{2H}} t_{2H} + \frac{dq_{1A}^B}{dw} w$$

$$q_{3A}^B = C_{3A} + \frac{dq_{3A}^B}{dt_{1A}} t_{1A} + \frac{dq_{3A}^B}{dt_{1H}} t_{1H} + \frac{dq_{3A}^B}{dt_{2H}} t_{2H} + \frac{dq_{3A}^B}{dw} w$$

$$Q_A^B = C_{1A} + C_{3A} + \frac{dQ_A^B}{dt_{1A}} t_{1A} + \frac{dQ_A^B}{dt_{1H}} t_{1H} + \frac{dQ_A^B}{dt_{2H}} t_{2H} + \frac{dQ_A^B}{dw} w$$

$$q_{1A}^B - q_{1A}^M = C_{1A} - \frac{\alpha_{1A}}{2\beta_A} + \frac{d(q_{1A}^B - q_{1A}^M)}{\partial t_{1A}} t_{1A} + \frac{dq_{1A}^B}{dt_{1H}} t_{1H} + \frac{dq_{1A}^B}{dt_{2H}} t_{2H} + \frac{dq_{1A}^B}{dw} w$$

$$Q_A^B - Q_A^M = C_{1A} + C_{3A} - \frac{\alpha_{1A}}{2\beta_A} + \frac{d(Q_A^B - Q_A^M)}{\partial t_{1A}} t_{1A} + \frac{dQ_A^B}{dt_{1H}} t_{1H} + \frac{dQ_A^B}{dt_{2H}} t_{2H} + \frac{dQ_A^B}{dw} w$$

where C_{1A} and C_{3A} are constants which are independent of t_{1A}, t_{1H}, t_{2H} and w. Therefore, $q_{1A}^B - q_{1A}^M > 0$ if t_{1A} is sufficiently small relative to t_{1H}, t_{2H} and w. $Q_A^B - Q_A^M > 0$ and q_{3A}^B is large if t_{1A}, t_{2H} and w are sufficiently small relative to t_{1H}.

Q.E.D.

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