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Airline network choice and market coverage under high-speed rail competition

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ABSTRACT

While the existing literature has focused on the short-term impacts, this paper investigates the long-term impacts of high-speed rail (HSR) competition on airlines. An analytical model is developed to study how an airline may change its network and market coverage when facing HSR competition on trunk routes. We show that prior to HSR competition, an airline is more likely to adopt a fully-connected network and cover fewer fringe markets if the trunk market is large. Under HSR competition, the airline will, for a given network structure, have a greater incentive to cover more fringe (regional or foreign) markets if the trunk market is large, or the airline network is close to hub-and-spoke. Further, the airline will, for any given market coverage, move towards a hub-and-spoke network when the trunk market is large, or the number of fringe markets covered by the airline network is large. Both effects are more prominent when the decreasing rate of airline density economies is large. We further show that HSR competition can induce the airline to adopt network structure and market coverage that are closer to the socially optimal ones, thereby suggesting a new source of welfare gain from HSR based on its long-term impacts on airlines. Implications for operators, policy makers and specific countries (such as China) are also discussed.

1. Introduction

Over the past decades, high-speed rail (HSR) has become a growing phenomenon around the world. In countries like Japan, France, Spain, Germany, Italy, Belgium, the Netherlands, United Kingdom, and South Korea, HSR is already a major transport mode for millions of passengers every day. With its first HSR line being introduced in 2007, China has since developed the most extensive and most heavily used HSR network in the world (e.g., Fu et al., 2012). A number of countries including United States, India, Malaysia (and Singapore), Thailand, Russia and Brazil, are seriously considering their HSR development, some of which countries even have a clear plan of construction and financing on the table.

Other than passengers, airlines are another party that are strongly affected by the rapid development of HSR. With increased train speed, HSR has become a *de facto* substitute and effective competitor of air transport, especially for routes with distances less than 1000 km (e.g., Janic, 1993; Rothengatter, 2011). Examples abound where airlines have been forced to withdraw from, or cut back on, short-haul routes. Recent cases of air route cancellations include a number of Chinese

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domestic markets such as Nanjing-Shanghai, Zhengzhou-Xi'an, Changsha-Guangzhou and Wuhan-Nanjing. Deep cuts of airfare after the introduction of HSR service are also very common. For example, the market between Wuhan and Xiamen, two Chinese cities recently linked by HSR, saw an 80% drop in air ticket price (CAPA, 2013b). Due partly to HSR competition, the net profits of the three major Chinese airlines all saw big drops in 2013 (32% for Air China, 25% for China Eastern Airlines, and 24% for China Southern Airlines). In fact, China's HSR now moves twice as many passengers as its airlines (Bradsher, 2013). The Chinese carriers are not alone here: for the first time ever, HSR has outpaced air travel in Spain. Figures released by the National Statistics Institute (INE) in 2014 show that 1.9 million people used the country's extensive HSR (aka "AVE") network in January compared with 1.8 million people who bought plane tickets. These represent a 7.3% year-on-year drop for airplane travel and a 22% rise in high-speed rail journeys.

Capacity reduction and price cuts are both short-term responses by airlines when they confront the direct competition from HSR. Virtually all of the existing literature on air transport–HSR interaction has focused on such short-run impacts (see Givoni and Dobruszkes, 2013, for a recent review). For example, Gonzalez-Savignat, 2004 indicates that HSR service significantly reduces the market share of air transport when the two modes compete head-on. Park and Ha (2006) find that the opening of the first HSR line in South Korea has a significant (negative) impact on the domestic air transport industry. With a simulation model, Ivaldi and Vibes (2008) study the intramodal and intermodal (rail, road, and air) competition with price as the decision variable. Adler et al. (2010) use a game theory setting to analyze aviation-HSR competition in the medium-to-long distance transport markets. With a short-run model focusing on traffic and price, they conclude that the European Union should encourage development of the HSR network across Europe. Yang and Zhang (2012) show that if the objective of an HSR operator is to maximize a weighted sum of welfare and profit, both airfare and HSR fare fall as the weight on welfare rises; furthermore, airfare decreases, but HSR fare increases, in the airport access time.[1] Jiang and Zhang (2014) show that cooperation between airline and HSR reduces traffic in markets where prior modal competition occurs, but may increase traffic in other markets of the network.[2]

However, once established, competition from HSR will likely stay; therefore, airlines need to come up with strategies to compete against HSR in the long run. In this paper we examine, analytically, two long-term airline strategies: (i) network structure, and (ii) market coverage. The network structure, namely a "fully connected" (point to point) network or a hub-and-spoke network, involves a large amount of initial investment and once established, is hard to change (e.g., Oum et al., 1995). In the long run however, airlines can restructure their network structures. Usually, the network structure is relatively constant unless some major events, such as airline deregulation, happen.[3] Many carriers in the world, such as the Chinese airlines, are still using the fully-connected network (Zhang, 2010; Fu et al., 2012), and the fierce competition from HSR is likely to be such a major event that causes the carriers to switch from a fully-connected network to a hub-and-spoke network. As for the decision on market coverage, one of the most important features of air transport is its extensive network coverage. Unlike HSR, which is economically viable only for certain trunk routes due to substantial fixed costs involved in infrastructure building, airlines can serve many smaller markets, hence creating a much more extensive network from which some network-specific benefits (such as higher service frequency and economies of traffic density) are available. One possible competitive strategy by airlines is to target markets that they have previously ignored. These "fringe" markets (small regional markets and/or international markets) may be less profitable to serve than the domestic trunk markets, but they may nevertheless help airlines survive the HSR competition on the trunk routes.[4]

In this paper we study an airline's long-run responses of an airline when it faces the entry of HSR into its domestic trunk market (or when HSR is already in service, it faces an improvement of HSR competitiveness in terms of cost reduction and/or high service quality), with network structure and market coverage being its two potential strategies. Our analysis will specifically incorporate the possible diminishing returns in the benefits from higher traffic density. Academic literature has identified the benefits of higher traffic density on a particular route in terms of reduced cost per passenger (aka "economies of traffic density"). However, the observation that these benefits are likely to diminish as the airline's traffic on the route increases is less explored, a factor that is to be taken into account in the present paper. Our analysis shows that for a given network structure, when HSR enters the trunk route (or improves its competitiveness on the route), the airline will have a greater incentive to cover more fringe (regional, foreign) markets if the trunk market is larger or the airline network is closer to hub-and-spoke. On the other hand, for any given level of market coverage, it would be more likely for the airline to move towards hub-and-spoke network as a response to the HSR entry (or an increase in HSR competitiveness) when the trunk market is larger, or when the airline covers more fringe markets. Both effects are more prominent when the diminishing rate of the benefits from greater air traffic density is higher. We further demonstrate that the socially optimal levels of market coverage and network structure can be higher or lower than the privately optimal levels depending on the size of the trunk market. More importantly, we show that introducing (or enhancing) HSR competition can induce the airline to achieve market-coverage and network-structure levels that are closer to the socially optimal levels. We note that

[1] See Behrens and Pels (2012) and Martin et al. (2014) for recent empirical studies on the role of terminal access (among others) on the competition between HSR and air transport.

[2] For recent empirical work on competition and cooperation/integration between the two modes, see Albalate et al. (2014) and Roman and Martin (2014).

[3] The Airline Deregulation Act of 1978 has led most of major US airlines to shift from a fully-connected network to a hub-and-spoke network (e.g., Levine, 1987; Borenstein, 1992; Zhang et al., 2011). The deregulation of European airlines between 1993 and 1997 had a similar effect.

[4] CAPA (2013a) suggests that for Chinese airlines, international yields are often significantly lower than domestic yields, and international services are often unprofitable. Notice that so far, there is no HSR service between China and other countries.

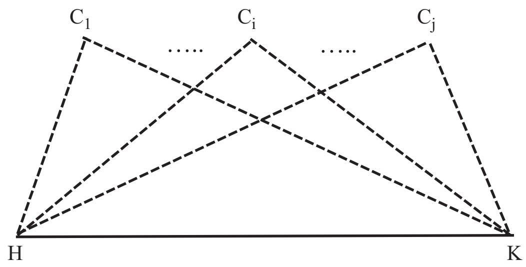

Fig. 1. Network structure.

this paper is the first analytical attempt to study the long-term strategies of airlines in the era of HSR competition. And these findings provide useful managerial and policy implications.

For the airlines, network structure can be a powerful competitive weapon in the long run. The fierce competition from HSR may be a trigger for the airlines that are still using fully-connected network to change their network structures. For example, focusing on the Chinese market, Fu et al. (2012) argue, qualitatively, that facing the competitive pressure from HSR, the Chinese airlines need to transform their current fully-connected networks to hub-and-spoke networks and rely more on demands from small- and medium-size airports as well as international markets. For the policy makers, we suggest that it is important to take into account the long-term impacts of HSR competition when they decide on regulations. Airline network choice is highly influenced by government regulations (including the international regulatory regimes), and different conclusions about airline regulations may be reached depending whether policy makers take into account the impacts of HSR competition or not. It should be noted that these results might be more relevant to certain markets (e.g., China) than others (e.g., Europe) due to the features that we choose to put into the model, but more general conclusions can follow with the extension of the framework.

The paper is organized as follows. Section 2 sets up the basic model. Section 3 analyzes airlines' long-term decisions of network structure and market coverage with and without HSR competition. Section 4 carries out welfare analysis and finally, Section 5 contains concluding remarks.

2. Model

Consider a network that is probably the simplest in which our main issues can be addressed. As depicted in Fig. 1, the transportation network has two major domestic cities H and K and a number of small homogeneous cities C_i.[5] There are one airline and one HSR operator[6]; both can serve the "trunk" route HK, but the other cities can be linked with H and K only by the airline. Here, C_i's can be small domestic cities or foreign cities.[7] When linked with the two major cities, a specific city C_i will generate two markets, namely C_iH and C_iK. To keep our discussion consistent, we refer to these markets as the "fringe" markets in what follows. For simplicity, we assume that there is no travel demand between C_i and C_j, $\forall i, j$.[8]

[5] Throughout this paper, we assume that there are a very large number of such small cities.

[6] It should be noted that this setting is quite restrictive. Reality is much more complicated, in particular we seldom see a "one airline" market structure in any country. This may cause our analytical results to be inconsistent with reality in a number of areas like pricing. There are four reasons for this simplification. First, the major motivation of this paper is the Chinese case, in which these assumptions are largely consistent with reality. On the one hand, some characteristics of the Chinese aviation market make the assumptions of monopoly airline somewhat reasonable. For example, the Big Three in China (Air China, China Eastern and China Southern) are all state-own enterprises, while two of them (China Eastern and China Southern) are members of the same global airline alliance (SkyTeam). In this case, even when we see more than one airline serving a market (Shanghai-Guangzhou, for instance, served by both China Eastern and China Southern), the result might not be very different from a monopoly case. On the other hand, low cost carriers are marginal in the Chinese context. The market shares of low cost carriers are almost negligible within China. Second, this is the first paper to theoretically analyze the long-term impacts of HSR competition on airline network. As the tradition of theoretical studies, it is necessary to make certain simplifications in order to accommodate new features. In fact, previous theoretical papers in air-HSR interactions also largely assume one-airline scenario (e.g., Yang and Zhang, 2012; Jiang and Zhang, 2014). Third, the difference in market structures has a stronger implication on some areas such as pricing, but should matter less in the long-term network decision, which is the focus of this paper. Last but not least, we do not attempt to make a one-off replication of reality in its exact form. The simplifying assumption is made clear so that the audience is well aware of the limitation of the analysis. The contribution is instead to provide a general framework, which can be extended and utilized in specific cases with methodologies like simulation to accommodate more particular features such as the two-sided market characteristic pointed out by the referee. But without this first step, the "reality analysis" will be baseless.

[7] In the case of small domestic cities, HSR cannot serve C_i because the fixed cost of serving such a market is much higher for the HSR than for the airline. In particular, it is more costly for the HSR to build its infrastructure (tracks, etc.). Therefore, it requires a larger market for the HSR to enter a market and be profitable. Airlines, on the other hand, are more flexible and nimble. Since they normally do not need to directly pay for the infrastructure (airports, air traffic control, etc.) it is relatively easy for them to enter or exit a particular market. In the case of foreign cities, HSR cannot reach C_i mainly due to geographical or political reasons. Note that this setting only fits small domestic cities but not foreign cities in the European context, given the extensive cross-border HSR links in the Eurail system. Admittedly, if we take into account the medium-speed and low-speed trains, the railway network coverage will increase significantly. However, to achieve operational efficiency, the trend for HSR development is dedicated line (e.g., China, which is the major motivation of this paper). In other words, the complementarity between HSR and conventional rails is decreasing (Hsu and Wang, 1997; Hsu et al., 2010). Besides, due to the huge difference in speed, conventional railway is generally not considered as a viable competitor of airlines.

[8] This assumption is reasonable because the demand between any two small domestic cities is usually very low or negligible, and a route between two foreign cities may not be served by the airline due, for instance, to the lack of traffic rights.

On the demand side, following Czerny and Zhang (2015) we use B^k to denote the (gross) travel benefit to passengers in market k, with $B^k = B^k(q_A^k, q_R^k)$. The benefit functions are characterized by $\partial B^k/\partial q_o^k > 0$ and $\partial^2 B^k \Big/ \partial q_o^{k^2} \leqslant 0$, with subscripts $o = A, R$ representing the transport operators (A for airline, R for rail). Thus, the benefit is concave in passenger quantity.[9] To avoid further complication, $\partial^2 B^k \Big/ \partial q_o^{k^2}$ is taken as constant. Further, the "full price" of travelling is given by:

$$P_o^k = p_o^k + t_o^k \tag{1}$$

where p_o^k is the ticket price charged by operator o in market k, while t_o^k are the other travel costs for a passenger.[10]

Consumer surplus, denoted CS, can be written as $CS = \sum_k \left(B^k - \sum_o P_o^k q_o^k\right)$. Passenger demand is determined by the equilibrium condition $\partial CS/\partial q_o^k = 0$. This implies that $\partial B^k \Big/ \partial q_o^k = P_o^k$, where the left-hand side is the marginal benefit of having one more passenger of a particular mode in a particular market, while the right-hand side is the full price. This, together with (1), lead to[11]

$$p_o^k = \frac{\partial B^k}{\partial q_o^k} - t_o^k \tag{2}$$

Consider first the fringe markets that are not subject to the HSR competition. The small (foreign) cities can be served by the airline in two different types of network structure: fully connected (FC) or hub-and-spoke (HS). When congestion at airports H and K is not an issue (as is the case for the present paper), it can be easily seen that the airline will use only one of the two major cities as its hub. For simplicity (and without loss of generality) we assume that the hub airport is H if the HS network is adopted.

We further assume that the number of passengers is the same, and given by S, across all the fringe markets, and that the passengers' willingness-to-pay in these cities is the same and given by G. As a consequence, $B^{k\prime}(q_A^k) = G$ and $B^{k\prime\prime}(q_A^k) = 0$, $\forall k \neq T$, where T denotes the trunk market HK.[12] Since air is the only transport mode in these fringe markets, the monopoly carrier will charge passengers a price that will extract all their surpluses. For simplicity we assume that if a small city is covered, it will be linked with both H and K and the resulting two markets are symmetric.

Given the symmetry, under the FC network the airfares are the same for both markets as:

$$p_A^{iL} = G - t_A^i \tag{3}$$

Hereafter in the superscripts we use i as a substitute for C_i.

Under the HS network, on the other hand, the C_iH and C_iK markets are no longer symmetric. So the ticket prices are:

$$p_A^{iH} = G - t_A^i \tag{4}$$

$$p_A^{iK} = G - t_A^i - t_A^T - \mu \tag{5}$$

where μ denotes the layover time for the hub connection. Assume that t_A^i is the same across all the small (foreign) cities, and normalize $G - t_A^i = 1$. Therefore, we have $p_A^{iL} = 1$, $p_A^{iH} = 1$ and $p_A^{iK} = 1 - \tau$, where $\tau = t_A^T + \mu$.

In contrast to the fringe markets, the passengers in the trunk market HK are heterogeneous and thus their willingness-to-pay is not constant. A larger market usually faces a more diverse customer base. Furthermore, this market is subject to the potential competition from an HSR operator. Therefore, the inverse demand is a function of both the air traffic and the HSR traffic $P_A^T = \partial B^T/\partial q_A^T$, with $\partial^2 B^T \Big/ \partial q_A^{T^2} < 0$, $\partial^2 B^T \Big/ \partial q_R^{T^2} < 0$ and $\partial^2 B^T/\partial q_A^T \partial q_R^T < 0$.

For a given route, the operating cost per passenger, $C_o\left(Q_o^l\right)$ (>0), depends on the total traffic level on a particular route l (when the airline adopts an HS network, it is equal to all the traffic through this route), with $C_o'\left(Q_o^l\right) < 0$ and $C_o''\left(Q_o^l\right) \geqslant 0$.

[9] This general functional form also explicitly incorporates the impacts of frequencies and "scheduled delay" (Douglas and Miller, 1974). The frequency of a transport mode is a function of the traffic volume of this mode by nature. For example, if we assume that the seat capacities of both transport modes are exogenously given, then frequencies would be linear functions of the corresponding traffic volumes. The benefits that passengers obtain from higher frequencies are thus functions of the two traffic volumes and can be easily accommodated into B^k.

[10] The most important component of these costs is the travel time. Numerous studies have pointed out travel time as one of the most important factors that affect passengers' travel decisions (e.g., Gronau, 1970) and also their choice of travel modes (e.g., Roman et al., 2007). It should be noted that this modeling (i.e., a monetary value of travel cost instead of real travel time in the full price function) allows the flexibility to accommodate the fact that the same amount of time spent in air travel and in train travel might imply different values for the passengers. In particular, as correctly pointed out by an anonymous referee, "one hour flying (incl. check-in, security, waiting etc.) is normally waste of time, while one hour in a train is productive or consumptive time, so the willingness-to-pay (might) differ vastly".

[11] With this setting, we only consider the average prices and ignore the dynamics of pricing practices in both the air and the rail sectors. We are well aware of the fact that both sectors (especially the airlines) are heavily involved in dynamic pricing. However, it is not the focus of this paper. Therefore, following a series of previous work (e.g., Adler et al., 2010; Yang and Zhang, 2012), we do not take this feature into account so as to maintain the simplicity and clarity of the analytical results.

[12] The assumption is made for the simplification of analysis. To check the robustness of the analytical results we will, in Appendix A, relax this assumption and consider heterogeneous passengers and hence downward-sloping demands for the fringe markets. It is shown that the major results still hold.

The former inequality shows the economies of traffic density in both air transport and HSR (see Jiang and Zhang, 2014, and the references cited there), while the latter is an explicit modeling of the decreasing rate of the density economies (e.g., Brueckner and Spiller, 1994).[13] It should be noted that the second-order derivative of $C_o\left(Q_o^I\right)$ is largely ignored by the literature, due to the fact that most of the results only rely on the first-order derivative (i.e., the economies of traffic density). However, the ability to use larger, more efficient aircraft and to spread end point fixed costs is often cited as the driving force of airlines' economies of traffic density. It then is expected that the marginal benefit of increasing traffic density should demonstrate a decreasing trend. For analytical clarity we further assume that $C''_A\left(Q_A^I\right)$ is constant and equal to θ: Specifically, $C_A\left(Q_A^I\right) = \alpha - \left(\beta - \frac{\theta}{2}Q_A^I\right)Q_A^I$ and hence $C'_A\left(Q_A^I\right) = -\beta + \theta Q_A^I$, where θ can be interpreted as the decreasing rate of the density economies.[14]

Following Oum et al. (1995) we consider hubbing as a continuous decision denoted using the "infinitesimal hubbing" parameter δ, where δ is bounded by 0 and 1. In particular, when $\delta = 0$, the airline adopts a pure FC network; while when $\delta = 1$, the airline network is purely HS. In our setting, since all fringe cities are identical, δ can be interpreted as the percentage of traffic in any fringe market that is connected with the major cities with an HS network.[15] So the final profit function of the airline is:

$$\pi_A = q_A^T\frac{\partial B^T}{\partial q_A^T} + 2NS - (q_A^T + \delta NS)C_A(q_A^T + \delta NS) - N(S + \delta S)C_A(S + \delta S) - \delta NS\tau - N(S - \delta S)C_A(S - \delta S) \tag{6}$$

The airline first makes the long-term decisions about the network structure δ and the market coverage N. Given these long-term decisions, the airline then decides on the traffic volume in the trunk market HK. If the HSR is also in the trunk market, the two operators engage in Cournot competition. We examine the subgame perfect Nash equilibrium of this two-stage game.

3. Analysis of airline decisions

3.1. The trunk market

First consider the last stage of the airline's decision-making. The first-order condition with respect to the trunk traffic of the airline is given by:

$$\frac{\partial B^T}{\partial q_A^T} + q_A^{T^*}\frac{\partial^2 B^T}{\partial q_A^{T^2}} - C_A(q_A^{T^*} + \delta NS) - (q_A^{T^*} + \delta NS)C'_A(q_A^{T^*} + \delta NS) = 0 \tag{7}$$

where superscript $*$ denotes the privately optimal level. The second-order condition, $\partial^2\pi_A/\partial q_A^{T^2} \leqslant 0$, is assumed to hold.[16] This condition creates an upper bound for q_A^T, which is generally reasonable as long as the density economies remain moderate (Brueckner, 2001).

Lemma 1. *When the trunk market is sufficiently large, it is possible that: (i) covering more fringe markets reduces the number of trunk market passengers served by the airline for any given network structure; (ii) moving further towards a hub-and-spoke network decreases the number of trunk market passengers served by the airline for any given level of market coverage.*

Proof. Taking derivative of (7) with respect to N yields:

$$\frac{\partial^2\pi_A}{\partial q_A^{T^2}}\frac{\partial q_A^{T^*}}{\partial N} - \delta S\left[2C'_A(q_A^{T^*} + \delta NS) + (q_A^{T^*} + \delta NS)C''_A\right] = 0$$

Since $\partial^2\pi_A\Big/\partial q_A^{T^2} \leqslant 0$, we have $\partial q_A^{T^*}/\partial N < 0$ only when $2C'_A(q_A^{T^*} + \delta NS) + (q_A^{T^*} + \delta NS)C''_A > 0$.

Similarly, taking derivative of (7) with respect to δ, we have

$$\frac{\partial^2\pi_A}{\partial q_A^{T^2}}\frac{\partial q_A^{T^*}}{\partial \delta} - NS\left[2C'_A(q_A^{T^*} + \delta NS) + (q_A^{T^*} + \delta NS)C''_A\right] = 0$$

[13] Brueckner and Spiller (1994) test a few specifications for the marginal cost of US airlines on a particular spoke, including a quadratic function of the spoke traffic level. This specification has the highest log likelihood value (indicating best fit), and the coefficient of the quadratic term is positive and statistically significantly different from zero.

[14] Note that this functional form is not necessarily needed for many of our analytical results, but it will be helpful for the clarity of analysis and economic interpretation.

[15] δ may also be interpreted as the percentage of fringe cities that are connected with the major cities with an HS network, which will make the airline profit function slightly different. However, it can be easily shown that all the results hold under this alternative specification. Detailed analysis is available upon request.

[16] This condition does not hold automatically due to the cubic nature of the cost function.

Given that $\partial^2\pi_A \big/ \partial q_A^{T^2} \leqslant 0$, we have $\partial q_A^{T^*}/\partial\delta < 0$ also only when $2C'_A\left(q_A^{T^*}+\delta NS\right)+\left(q_A^{T^*}+\delta NS\right)C''_A > 0$.

Denote $2C'_A\left(q_A^{T^*}+\delta NS\right)+\left(q_A^{T^*}+\delta NS\right)C''_A = \Psi$, and we have $\partial\Psi/\partial q_A^{T^*} = 3C''_A > 0$. In other words, when the trunk market is sufficiently large, thus the equilibrium $q_A^{T^*}$, it is possible to have $2C'_A\left(q_A^{T^*}+\delta NS\right)+\left(q_A^{T^*}+\delta NS\right)C''_A > 0$. □

This lemma is intuitive. Since the benefit of higher traffic density on a particular route is decreasing, there should be an optimal density level for any route. When the trunk market is large, the airline is able to achieve a high level of density on the trunk route without rerouting passengers from other markets through the HS network. In effect, if the trunk market size is sufficiently large, more traffic from other markets (either by increasing the HS level or covering more fringe markets) might actually result in the total traffic on the trunk route being farther away from the optimal level, even forcing the airline to retreat from the trunk market. As to be seen in the following discussion, this mechanism is the major force that connects the trunk market with the fringe markets in the airline's network.

3.2. Long-term decisions in the absence of HSR competition

Turn now to the long-term decisions, network structure and market coverage. In our analysis here, they are independently decided in the sense that when we consider one decision, the other is held constant.[17] Focus first on the case of no HSR competition. The airline is then a monopoly in all the markets considered, and its network structure and market coverage depend on the interactions between the trunk market and the fringe markets. According to the Envelope Theorem, we can derive its first-order conditions with respect to N and δ as:

$$2S - \delta S\tau - \delta SC_A\left(q_A^{T^*}+\delta N^*S\right) - \delta S\left(q_A^{T^*}+\delta N^*S\right)C'_A\left(q_A^{T^*}+\delta N^*S\right) - (S+\delta S)C_A(S+\delta S) - (S-\delta S)C_A(S-\delta S) = 0 \quad (8)$$

$$\begin{aligned} &-NS\left[\tau + C_A\left(q_A^{T^*}+\delta^*NS\right)+\left(q_A^{T^*}+\delta^*NS\right)C'_A\left(q_A^{T^*}+\delta^*NS\right)+C_A(S+\delta^*S)+S(1+\delta^*)C'_A(S+\delta^*S)+C_A(S-\delta^*S)\right.\\ &\quad \left.-S(1-\delta^*)C'_A(S-\delta^*S)\right] = 0 \end{aligned} \quad (9)$$

Again, the second-order conditions are assumed to hold. In particular, we need to assume that $\partial^2\pi_A/\partial N^2 \leqslant 0$ and $\partial^2\pi_A/\partial\delta^2 \leqslant 0$.

Proposition 1. *Prior to the entry of HSR in the trunk market, the airline is more likely to: (i) cover fewer fringe markets for a given network; (ii) adopt an FC network for a given number of fringe markets if the trunk market is sufficiently large.*

Proof. For Eq. (8) to hold, $q_A^{T^*}+\delta N^*S$ needs to be constant. Therefore, the larger the trunk market is, the larger $q_A^{T^*}$ will be, and the smaller N^* needs to be for any given δ.

Taking the derivative of Eq. (9) with respect to $q_A^{T^*}$, we have

$$\frac{\partial^2\pi_A}{\partial\delta^2}\frac{\partial\delta^*}{\partial q_A^{T^*}} - NS\left[2C'_A\left(q_A^{T^*}+\delta^*NS\right)+\left(q_A^{T^*}+\delta^*NS\right)C''_A\right] = 0$$

When the trunk market and thus $q_A^{T^*}$ is sufficiently large, $2C'_A\left(q_A^{T^*}+\delta^*NS\right)+\left(q_A^{T^*}+\delta^*NS\right)C''_A$ becomes positive. Since $\partial^2\pi_A/\partial\delta^2 \leqslant 0$, it means that $\partial\delta^*/\partial q_A^{T^*} < 0$ under such circumstance. In other words, when the trunk market is sufficiently large, δ^* needs to be small for any given N. □

Proposition 1 provides another explanation for why HS network system does not exist in some of the major aviation markets in the world. When an airline is operating in large trunk markets, it may lack the incentive to work hard to develop an HS system and cover more fringe markets. Given that the trunk market is sufficiently large enough to realize low unit operating costs, concentrating traffic from fringe markets to the trunk route won't reduce the marginal operating cost very much. This feature describes the Chinese aviation market well. First, China has a number of trunk markets with sizable demands, such as Beijing-Shanghai, Shanghai-Guangzhou, and Beijing-Shenzhen.[18] Due to regulations and state ownership, a large fraction of the Chinese domestic markets is still dominated by one or two airlines (e.g., Zhang et al., 2014), meaning that these dominant airlines can achieve density economies on the trunk routes to a very high degree. Second, airspace control by the military is an important feature of the Chinese aviation industry as they frequently ground air flights. This significantly limits the potential of the Chinese airlines to exploit traffic density. Therefore, all of the Chinese airlines are still adopting *de facto* FC networks for their domestic traffic.

[17] We note that the results obtained in this section not only shed light for the circumstances where one of the two strategies is not readily available, but also largely hold even if these two long-term decisions are made simultaneously.

[18] Among the world's 50 busiest routes based on the total number of seats per month flown in both directions as of April 2014, eight are domestic routes in China.

3.3. Long-term decisions under HSR competition

Examine now the impact of HSR competition on the airline's choice of network structure and market coverage. Denote the competitiveness of HSR with a continuous parameter γ ($\gamma \geqslant 0$): When $\gamma = 0$, HSR is noncompetitive versus air transport and is thus excluded from the trunk market.[19] The larger the γ is, the more competitive the HSR (versus air transport) is in the trunk market.[20] In other words, the increase of γ from 0 to any positive number can also be interpreted as the entry of HSR into the trunk market. Therefore, other things being equal, we should have $\partial q_R^{T^*}/\partial\gamma > 0$ and $\partial q_A^{T^*}/\partial\gamma < 0$.

From Eqs. (8) and (9), the following Propositions 2 and 3 can be derived.

Proposition 2. *For given airline network structure, the HSR entry or an increase of HSR competitiveness will push the airline to cover more fringe markets when the trunk market is sufficiently large, and/or the airline network is close to HS. This effect is more prominent when the decreasing rate of density economies is large.*

Proof. Taking derivative of (8) with respect to γ yields:

$$-\delta S\left[2C_A'\left(q_A^{T^*} + \delta N^* S\right) + \left(q_A^{T^*} + \delta N^* S\right)C_A''\right]\frac{\partial q_A^{T^*}}{\partial \gamma} + \frac{\partial^2 \pi_A}{\partial N^2}\frac{\partial N^*}{\partial \gamma} = 0$$

Given that $\partial^2\pi_A/\partial N^2 \leqslant 0$, we have $\partial N^*/\partial\gamma > 0$ as long as

$$2C_A'\left(q_A^{T^*} + \delta N^* S\right) + \left(q_A^{T^*} + \delta N^* S\right)C_A'' > 0$$

Again, this is more likely when the trunk market is larger and hence $q_A^{T^*}$ is larger.

Besides, we have $\partial\Psi/\partial\delta = 3N^* S C_A'' > 0$, which means that it is more likely to have $\Psi > 0$ when δ is large.

By imposing the quadratic form of $C_A\left(Q_A^I\right)$, we get

$$2C_A'\left(q_A^{T^*} + \delta N^* S\right) + \left(q_A^{T^*} + \delta N^* S\right)C_A'' = -2\beta + 3\theta\left(q_A^{T^*} + \delta N^* S\right)$$

It is clear that the increase of $q_A^{T^*}$ and/or δ will have a larger impact on Ψ with a larger θ. □

Proposition 3. *For given airline market coverage, the HSR entry or an increase of the HSR competitiveness will move the airline towards an HS network when the trunk market is sufficiently large, and/or the airline covers a larger number of fringe markets. This effect is more prominent when the decreasing rate of density economies is large.*

Proof. Taking the derivative of (9) with respect to γ yields

$$-NS\left[2C_A'\left(q_A^{T^*} + \delta^* NS\right) + \left(q_A^{T^*} + \delta^* NS\right)C_A''\right]\frac{\partial q_A^{T^*}}{\partial \gamma} + \frac{\partial^2 \pi_A}{\partial \delta^2}\frac{\partial \delta^*}{\partial \gamma} = 0$$

Given that $\partial^2\pi_A/\partial\delta^2 \leqslant 0$, we have $\partial\delta^*/\partial\gamma > 0$ as long as

$$2C_A'\left(q_A^{T^*} + \delta^* NS\right) + \left(q_A^{T^*} + \delta^* NS\right)C_A'' = -2\beta + 3\theta\left(q_A^{T^*} + \delta^* NS\right) > 0$$

Again, this is more likely when the trunk market is larger and hence $q_A^{T^*}$ is larger.

Besides, we have $\partial\Psi/\partial N = 3\delta^* S C_A'' > 0$, which means that it is more likely to have $\Psi > 0$ when N is large.

By imposing the quadratic form of $C_A(Q_A^I)$, we get

$$2C_A'\left(q_A^{T^*} + \delta N^* S\right) + \left(q_A^{T^*} + \delta N^* S\right)C_A'' = -2\beta + 3\theta\left(q_A^{T^*} + \delta^* NS\right)$$

It is clear that the increase of $q_A^{T^*}$ and/or N will have a larger impact on Ψ with a larger θ. □

Propositions 2 and 3 describe how an airline will respond to the HSR entry (or an increase in HSR competitiveness) in its trunk market. The larger the trunk market is, the more important it is to the airline. As a result, the airline will have a greater incentive to move to an HS network and cover more fringe markets, so that it can boost up traffic on the trunk route to compete with the HSR. From the propositions we can also see that the two strategies are mutually reinforcing: when more fringe markets are covered, to move closer to the HS network will direct more traffic to the trunk route. On the other hand, when the network is closer to the HS system, covering one more fringe market can have a similar effect. Besides, when the decreasing

[19] It can also be interpreted as the case when no HSR project is viable in the trunk market due to various reasons such as technology and cost.

[20] For a particular HSR, the increase of γ may be due to improvements in technology, operation or management. For example, due to safety concern, many of the HSR lines in China are running at a speed far below the maximum design level, which means that it is feasible to increase the attractiveness of HSR travel (versus air travel) by increasing operating speed with (for example) improved management.

rate of the airline's density economies is large, the decrease of airline traffic on the trunk route (due to the entry or competitiveness increase of the HSR) will significantly increase the benefit of higher traffic density, thus increasing the incentive of the airline to funnel more traffic onto the trunk route.

The prediction of Proposition 2 appears to fit the case of China quite well. Facing the competition pressure from a rapidly growing HSR sector, most of the Chinese airlines are now seeking opportunities abroad and avidly developing their international markets.[21] It is argued that among all the major airlines in China, Air China should be the least affected by HSR, since it has the highest exposure to international markets (Wu and Ross, 2013). Other examples include Spain, where Iberia Airline increased its market coverage and its shares in other domestic markets after the opening of the Madrid-Barcelona HSR link (Jiménez and Betancor, 2011), and Japan. In Japan, both All Nippon Airways and Japanese Airlines paid more attention to the international markets when they faced an increasing extent of competition from HSR Shinkansen in the 1980s and 1990s.

It has been reported that the HSR market share on routes where air competition is very strong does not reach the levels usually obtained in previous European high-speed links where competition from air transport was less important (Lopez Pita et al., 2012). One possible explanation for this observation is that the predictions all focused on short-run decisions such as traffic and price, but the airlines have actually adopted long-run strategies to battle HSR on important trunk routes. In other words, this paper suggests that in order to predict or evaluate the impacts of HSR on the air sector (and also the total social welfare, to be discussed in the next section), the longer-term analysis is also needed.

We can see a clear difference that HS network makes for the airline from the comparison between European and Asian cases. Despite a short flying distance of only 500 km, half of the travelers on the Madrid-Barcelona route fly. This is in contrast to air transportation's 20% market share on the Tokyo-Osaka route (515 km) and 38% on the Guangzhou-Changsha route (550 km). The distance from London to Paris is only 322 km, but air transport has preserved 25% market share. In contrast, airlines in Asia are unable to compete with HSR on a short-haul route like London-Paris (in effect, they exited from such a route). This significant difference might partially be due to the fact that European airlines have developed a mature HS system linking "domestic" (European) and international markets, while most of the Asian airlines (especially those in Japan and China) are still using FC networks.

4. Welfare impact

This section examines the long-term effect of air-HSR competition on social welfare. It is expected that there may be a difference between the socially and privately optimal levels for airline network structure and market coverage. It would be of interest to policy makers to see whether and how this difference will be affected by the HSR competition.

Social welfare is given by the following equation:

$$\begin{aligned} W &= CS + \pi_A + \pi_R \\ &= B^T(q_A^T, q_R^T) + 2NS - (q_A^T + \delta NS)C_A(q_A^T + \delta NS) - N(S+\delta S)C_A(S+\delta S) - \delta NS\tau - N(S-\delta S)C_A(S-\delta S) - q_R^T C_R(q_R^T) \end{aligned} \quad (10)$$

Given δ and N, the socially optimal airline trunk traffic is characterized by

$$\frac{\partial B^T}{\partial q_A^T} - C_A(q_A^{T^{**}} + \delta NS) - (q_A^{T^{**}} + \delta NS)C'_A(q_A^{T^{**}} + \delta NS) = 0 \quad (11)$$

where superscript $**$ denotes the socially optimal level. The second-order condition, $\partial^2 W / \partial q_A^{T^2} \leqslant 0$, is again assumed to hold.

Comparing Eqs. (7) and (11), we can reach the following lemma.

Lemma 2. *For any given airline network structure and market coverage, in the trunk market the socially optimal air traffic level is higher than the privately optimal air traffic level. The difference between these two traffic levels is reduced however, after HSR enters, or increases its competitiveness, in the trunk market.*

Proof. Substituting $q_A^{T^*}$ into the left-hand side of Eq. (11), we have

$$\begin{aligned} \frac{\partial B^T}{\partial q_A^T} - C_A(q_A^{T^*} + \delta NS) - (q_A^{T^*} + \delta NS)C'_A(q_A^{T^*} + \delta NS) &> \frac{\partial B^T}{\partial q_A^T} + q_A^{T^*}\frac{\partial^2 B^T}{\partial q_A^{T^2}} - C_A(q_A^{T^*} + \delta NS) - (q_A^{T^*} + \delta NS)C'_A(q_A^{T^*} + \delta NS) = 0 \\ &= \frac{\partial B^T}{\partial q_A^T} - C_A(q_A^{T^{**}} + \delta NS) - (q_A^{T^{**}} + \delta NS)C'_A(q_A^{T^{**}} + \delta NS) \end{aligned}$$

according to Eq. (7) and $\partial^2 B^T / \partial q_A^{T^2} \leqslant 0$.

[21] In October 2013, international traffic at the Chinese "Big Three" carriers – Air China, China Southern Airlines and China Eastern Airlines – increased by 23% (compared with 18% one year earlier), significantly outpacing their mid-single-digit growth in domestic traffic (Chiu, 2013). A significant number of new international routes have been opened by the Chinese airlines during the past few years when HSR were entering domestic trunk routes.

Since $\partial^2 W \big/ \partial q_A^{T^2} \leqslant 0$, we should have $q_A^{T^{**}}(\delta, N) > q_A^{T^*}(\delta, N),\ \forall \delta, N$.

Denote $\Lambda(q_A^T) = \partial B^T / \partial q_A^T - C_A(q_A^T + \delta NS) - (q_A^T + \delta NS)C_A'(q_A^T + \delta NS)$. When γ increases, $q_A^{T^*}$ decreases, thus $\left| q_A^{T^*} \partial^2 B^T \big/ \partial q_A^{T^2} \right|$ decreases (since $\partial^2 B^T \big/ \partial q_A^{T^2}$ is constant). This means that $\Lambda(q_A^{T^*}) - \Lambda(q_A^{T^{**}})$ decreases. Therefore, $q_A^{T^{**}}(\delta, N) - q_A^{T^*}(\delta, N)$ should also be smaller. □

We can further derive the airline's first-order conditions with respect to N and δ as:

$$2S - \delta S\tau - \delta SC_A(q_A^{T^{**}} + \delta N^{**}S) - \delta S(q_A^{T^{**}} + \delta N^{**}S)C_A'(q_A^{T^{**}} + \delta N^{**}S) - (S + \delta S)C_A(S + \delta S) - (S - \delta S)C_A(S - \delta S) = 0 \quad (12)$$

$$\begin{aligned} &-NS\left[\tau + C_A(q_A^{T^{**}} + \delta^{**}NS) + (q_A^{T^{**}} + \delta^{**}NS)C_A'(q_A^{T^{**}} + \delta^{**}NS) + C_A(S + \delta^{**}S) + S(1 + \delta^{**})C_A'(S + \delta^{**}S) + C_A(S - \delta^{**}S)\right. \\ &\quad \left. -S(1 - \delta^{**})C_A'(S - \delta^{**}S)\right] = 0 \end{aligned} \quad (13)$$

These two equations are exactly the same as Eqs. (8) and (9) in structure, meaning that the difference between the socially and privately optimal levels of the long-term variables depends mainly on their relationships with the trunk market traffic.

As discussed in Lemma 1, covering more fringe markets and/or increasing the level of HS network might cause the airline to increase or decrease its provision of traffic to the trunk market, depending on the trunk market size. Since the (privately or socially) optimal levels of airline market coverage and network structure are closely related to the trunk market traffic, it is reasonable to see that this relationship also affects the difference between these optimal levels under profit maximization and welfare maximization.

Proposition 4. *The privately optimal levels of airline network structure and market coverage are both closer to the socially optimal levels after HSR enters, or increases its competitiveness, in the trunk market.*

Proof. Again from Lemma 2, for fixed δ we have

$$q_A^{T^*}(N^{**}) + \delta N^{**}S < q_A^{T^{**}}(N^{**}) + \delta N^{**}S = q_A^{T^*}(N^*) + \delta N^*S$$

And when γ increases, the difference between the left-hand side and the middle of the above inequality decreases. In other words, the function $q_A^{T^*}(N) + \delta NS$ gives out closer values with N^* and N^{**} when γ is larger, meaning that the difference between N^* and N^{**} must be smaller.

Denote

$$\begin{aligned} \Gamma(q_A^T, \delta) = &-NS\left[\tau + C_A(q_A^T + \delta NS) + (q_A^T + \delta NS)C_A'(q_A^T + \delta NS) + C_A(S + \delta S) + S(1 + \delta)C_A'(S + \delta S)\right. \\ &\left. + C_A(S - \delta S) - S(1 - \delta)C_A'(S - \delta S)\right] \end{aligned}$$

For fixed N, in equilibrium we need

$$\Gamma(q_A^{T^{**}}, \delta^{**}) = \Gamma(q_A^{T^*}, \delta^*) = 0$$

From Lemma 2 we have

$$\Gamma(q_A^{T^*}, \delta^{**}) \lesseqgtr \Gamma(q_A^{T^{**}}, \delta^{**}) = \Gamma(q_A^{T^*}, \delta^*)$$

and the inequality depends on whether Γ increases or decreases with q_A^T.

When γ increases, the difference between the left-hand side and the middle of the above inequality decreases. In other words, the function Γ gives out closer values with δ^* and δ^{**} when γ is larger, meaning that the difference between δ^* and δ^{**} must be smaller. □

Proposition 4 bears an important message to policy makers. It shows that introducing HSR as a competitor of air transport will not only have short-term benefits by inducing the air traffic to a level that improves social welfare, but also have long-term rewards by forcing the airline to adopt more socially efficient structure. The competition from HSR, once established, will persist and exert consistent pressures to the airline to increase its performance and efficiency. The existing literature has largely ignored this long-term aspect of the modal competition, thereby downplaying the benefits of HSR development. For example, most of the policy evaluation and simulation projects assume that the airlines will stick with their network structures and only adjust traffic and price after HSR comes into the market. Therefore, it is possible that the conclusions based on such analytical frameworks account for only a part of the impacts that will result from the introduction of HSR. The framework that is discussed in this paper, on the other hand, can potentially correct this bias and provide a more complete assessment for the modal competition between air and HSR.

5. Concluding remarks

In this paper we have investigated the long-term impacts of high-speed rail (HSR) competition on airlines. A theoretical model was developed to study how airline market coverage and network choice will respond to HSR competition on origin-destination trunk routes. We found that when HSR enters, or improves its competitiveness, in the trunk market, the airline will have a greater incentive to cover more regional (or foreign) markets if the trunk market is large, and/or the airline network is close to a hub-and-spoke system. Furthermore, for any given market coverage level, the airline tends to move towards a hub-and-spoke network (from a fully-connected network) when the trunk market is large, and/or the number of fringe markets covered by the airline is large. Both effects are more prominent when the decreasing rate of density economies is large. We further demonstrated that the socially optimal levels of market coverage and network structure can be higher or lower than the privately optimal levels, depending on the size of the trunk market. More importantly, we showed that introducing or enhancing HSR competition can induce the airline to reach market coverage and network structure levels that are closer to the socially optimal ones.

These results offer some important insights for airlines that are struggling with the competition from HSR, by helping them come up with longer-term strategies. Network structure can be a powerful competitive weapon in the long run. Nowadays it is almost a norm for full-service carriers to adopt a partial or full HS system. However, many carriers in the world, such as the Chinese airlines, are still using a fully-connected network. The fierce competition from HSR may be a trigger for these airlines to change their network structures. On the other hand, we might also expect to see some hubbing airlines move a bit back to a fully-connected network under certain circumstances. Furthermore, our results suggest to policy makers that it is important to take into account the long-term impacts of HSR competition when they decide on regulations. For instance, airline network choice is highly influenced by government regulations (including the international regulatory regimes), and different conclusions about airline regulations may be reached depending whether policy makers take into account the impacts of HSR competition or not.

It is well recognized that the analysis presented in this paper has been based on several assumptions. It would be interesting to see whether the predictions of the model still hold if these assumptions are relaxed in one way or another (we have made some attempts in Appendix A). Besides, given that HSR has existed in a few countries for a while, it would be an interesting venue for future study to empirically test some of the predictions of this paper. Moreover, the present paper considered the airline network but not the network of HSR. This generally reflects the current situation: it is easier and more flexible for the airlines to cover a larger network. Nonetheless, we can also see, in China (and some European countries like Spain to a lesser extent), that HSR is starting to develop its own network. Such a network has some distinctive features as compared to the airline network, and it might play a role in affecting the airlines' long-term network choice and market coverage. Examining the interaction of the two networks would be another interesting topic of future research. Finally, the modeling of this paper is relatively simple in that it omits a few important features such as conventional (medium to low speed) rail network, interactions of multiple airlines including low cost carriers, and dynamic pricing practices by the airline as well as the rail operator. This level of simplification fits better the Chinese case, which is the major motivation of this paper. But if we want to extend the analysis to some other cases such as the European market, these features might become more substantial and need to be taken into account, which potentially opens up another interesting venue for future studies.

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Appendix A

In the appendix we will relax the assumption that passengers are homogeneous in the fringe markets, which was imposed in the text. More specifically, we consider here that the fringe markets also face downward sloping demands (as the trunk market does), and we test whether the results in Section 3 still hold. Since the fringe markets are identical, they share the same benefit function: $B^k(q_A^k) = B^F(q_A^k), \forall k \neq T$ where superscript F stands for fringe markets. Given that the demand functions are determined by the consumer surplus equilibrium, we should also have $p^k(q_A^k) = p^F(q_A^k)$. Under this new setting, the airline profit function thus becomes:

$$\pi_A = q_A^T p_A^T(q_A^T, q_R^T) + \sum_{i=1}^{N}[q_A^{iH} p_A^F(q_A^{iH}) + q_A^{iK} p_A^F(q_A^{iK})] - \left(q_A^T + \delta\sum_{i=1}^{N} q_A^{iK}\right) C_A\left(q_A^T + \delta\sum_{i=1}^{N} q_A^{iK}\right) - \sum_{i=1}^{N}(q_A^{iH} + \delta q_A^{iK}) C_A(q_A^{iH} + \delta q_A^{iK}) - \delta N\tau\sum_{i=1}^{N} q_A^{iK} - \sum_{i=1}^{N}(1-\delta) q_A^{iK} C_A(q_A^{iK} - \delta q_A^{iK}) \quad \text{(A1)}$$

First consider the last stage of the airline's decision-making. The first order conditions with respect to the traffic levels for the airline in the trunk market as well as the fringe markets are given by Eqs. (A2)–(A4):

$$p_A^T(q_A^{T^*}, q_R^{T^*}) + q_A^{T^*}\frac{\partial P_A^T}{\partial q_A^T} - C_A\left(q_A^{T^*} + \delta\sum_{i=1}^{N} q_A^{iK^*}\right) - \left(q_A^{T^*} + \delta\sum_{i=1}^{N} q_A^{iK^*}\right)C_A'\left(q_A^{T^*} + \delta\sum_{i=1}^{N} q_A^{iK^*}\right) = 0 \quad \text{(A2)}$$

$$p_A^F\left(q_A^{iH^*}\right) + q_A^{iH^*}p_A^{F\prime}\left(q_A^{iH^*}\right) - \left[C_A\left(q_A^{iH^*} + \delta q_A^{iK^*}\right) + \left(q_A^{iH^*} + \delta q_A^{iK^*}\right)C_A'\left(q_A^{iH^*} + \delta q_A^{iK^*}\right)\right] = 0 \quad \text{(A3)}$$

$$\begin{aligned} &p_A^F\left(q_A^{iK^*}\right) + q_A^{iK^*}p_A^{F\prime}\left(q_A^{iK^*}\right) - \delta C_A\left(q_A^{T^*} + \delta\sum_{i=1}^{N} q_A^{iK^*}\right) - \delta\left(q_A^{T^*} + \delta\sum_{i=1}^{N} q_A^{iK^*}\right)C_A'\left(q_A^{T^*} + \delta\sum_{i=1}^{N} q_A^{iK^*}\right) \\ &\quad - \delta\left[C_A\left(q_A^{iH^*} + \delta q_A^{iK^*}\right) + \left(q_A^{iH^*} + \delta q_A^{iK^*}\right)C_A'\left(q_A^{iH^*} + \delta q_A^{iK^*}\right)\right] - (1-\delta)\left[C_A\left(q_A^{iK^*}\right) + q_A^{iK^*}C_A'\left(q_A^{iK^*}\right)\right] = 0 \end{aligned} \quad \text{(A4)}$$

Note that due to homogeneity of the fringe markets, we will have $q_A^{iH^*} = q_A^{H^*}$ and $q_A^{iK^*} = q_A^{K^*}$, $\forall i$. Therefore, Eqs. (A2)–(A4) can be written as:

$$P_A^T(q_A^{T^*}, q_R^{T^*}) + q_A^{T^*}\frac{\partial P_A^T}{\partial q_A^T} - C_A\left(q_A^{T^*} + \delta N q_A^{K^*}\right) - \left(q_A^{T^*} + \delta N q_A^{K^*}\right)C_A'\left(q_A^{T^*} + \delta N q_A^{K^*}\right) = 0 \quad \text{(A2}'\text{)}$$

$$P_A^F(q_A^{H^*}) + q_A^{H^*}P_A^{F\prime}(q_A^{H^*}) - [C_A(q_A^{H^*} + \delta q_A^{K^*}) + (q_A^{H^*} + \delta q_A^{K^*})C_A'(q_A^{H^*} + \delta q_A^{K^*})] = 0 \quad \text{(A3}'\text{)}$$

$$\begin{aligned} &P_A^F(q_A^{K^*}) + q_A^{K^*}P_A^{F\prime}(q_A^{K^*}) - \delta\left[C_A\left(q_A^{T^*} + \delta N q_A^{K^*}\right) - \left(q_A^{T^*} + \delta N q_A^{K^*}\right)C_A'\left(q_A^{T^*} + \delta N q_A^{K^*}\right)\right] \\ &\quad - \delta[C_A(q_A^{H^*} + \delta q_A^{K^*}) + (q_A^{H^*} + \delta q_A^{K^*})C_A'(q_A^{H^*} + \delta q_A^{K^*})] - (1-\delta)[C_A(q_A^{K^*}) + q_A^{K^*}C_A'(q_A^{K^*})] = 0 \end{aligned} \quad \text{(A4}'\text{)}$$

The second-order conditions are assumed to hold. This requires the Hessian Matrix of the airline profit with respect to the airline traffic levels in different markets to be negative semi-definite. From Eqs. (A2′)–(A4′), we can find out the relationships between the equilibrium traffic levels in the trunk market and the fringe markets, which are summarized in Lemma A1 as follows.

Lemma A1. *If the trunk market is sufficiently large, the increase of traffic for the trunk market will decrease both types of fringe market traffic, for any given network structure and market coverage.*

Proof. Taking derivative of (A2′) with respect to $q_A^{T^*}$, we have

$$\frac{\partial^2\pi_A}{\partial q_A^{T^2}} - \delta N\left[2C_A'\left(q_A^{T^*} + \delta N q_A^{K^*}\right) + \left(q_A^{T^*} + \delta N q_A^{K^*}\right)C_A''\right]\frac{\partial q_A^{K^*}}{\partial q_A^{T^*}} = 0$$

Given that $\partial^2\pi_A/\partial q_A^{T^2} \leqslant 0$ due to the second order condition, if $2C_A'\left(q_A^{T^*} + \delta N q_A^{K^*}\right) + \left(q_A^{T^*} + \delta N q_A^{K^*}\right)C_A'' \geqslant 0$, we have $\partial q_A^{K^*}/\partial q_A^{T^*} \leqslant 0$.

Similarly, Taking derivative of (A3′) with respect to $q_A^{H^*}$, we have

$$\frac{\partial^2\pi_A}{\partial q_A^{H^2}} - \delta[2C_A'(q_A^{H^*} + \delta q_A^{K^*}) + (q_A^{H^*} + \delta q_A^{K^*})C_A'']\frac{\partial q_A^{K^*}}{\partial q_A^{H^*}} = 0$$

Since $\partial^2\pi_A/\partial q_A^{H^2} \leqslant 0$ due to the second order condition and $2C_A'(q_A^{H^*} + q_A^{K^*}) + (q_A^{H^*} + q_A^{K^*})C_A'' < 0$, we have $\partial q_A^{K^*}/\partial q_A^{H^*} > 0$. Reciprocally we should always have $\partial q_A^{H^*}/\partial q_A^{K^*} > 0$.

Therefore, if $2C_A'\left(q_A^{T^*} + \delta N q_A^{K^*}\right) + \left(q_A^{T^*} + \delta N q_A^{K^*}\right)C_A'' \geqslant 0$, we also have $\partial q_A^{H^*}/\partial q_A^{T^*} \leqslant 0$.

Denote $2C_A'\left(q_A^{T^*} + \delta N q_A^{K^*}\right) + \left(q_A^{T^*} + \delta N q_A^{K^*}\right)C_A'' = \Phi$, and we have $\partial\Phi/\partial q_A^{T^*} = 3C_A'' > 0$. □

Regarding the long-term decisions, we can, according to the Envelope Theorem, derive the first-order conditions of the airline with respect to N and δ as:

$$\begin{aligned} &\left[q_A^{H^*}P_A^F(q_A^{H^*}) + q_A^{K^*}P_A^F(q_A^{K^*})\right] - \delta q_A^{K^*}C_A(q_A^{T^*} + \delta N^* q_A^{K^*}) - \delta q_A^{K^*}(q_A^{T^*} + \delta N^* q_A^{K^*})C_A'(q_A^{T^*} + \delta N^* q_A^{K^*}) \\ &\quad - (q_A^{H^*} + \delta q_A^{K^*})C_A(q_A^{H^*} + \delta q_A^{K^*}) - (1-\delta)[q_A^{K^*}C_A(q_A^{K^*})] = 0 \end{aligned} \quad \text{(A5)}$$

$$-Nq_A^{K^*}C_A\left(q_A^{T^*}+\delta^*Nq_A^{K^*}\right)-Nq_A^{K^*}\left(q_A^{T^*}+\delta^*Nq_A^{K^*}\right)C_A'\left(q_A^{T^*}+\delta^*Nq_A^{K^*}\right)+Nq_A^{K^*}\left[C_A(q_A^{K^*})-C_A(q_A^{H^*}+\delta^*q_A^{K^*})\right.$$
$$\left.-(q_A^{H^*}+\delta^*q_A^{K^*})C_A'(q_A^{H^*}+\delta^*q_A^{K^*})\right]=0 \tag{A6}$$

Again, second-order conditions are assumed to hold. In particular, we need to assume that $\partial^2\pi_A/\partial N^2\leqslant 0$ and $\partial^2\pi_A/\partial\delta^2\leqslant 0$, respectively.

From Eqs. (A5) and (A6), we can prove that Propositions 2 and 3 still hold.

Proof of Proposition 2. Taking derivative of (A5) with respect to γ, we have

$$-\delta q_A^{K^*}\left[2C_A'(q_A^{T^*}+\delta N^*q_A^{K^*})+(q_A^{T^*}+\delta N^*q_A^{K^*})C_A''+\hat{x}\frac{\partial q_A^{H^*}}{\partial q_A^{T^*}}+\hat{y}\frac{\partial q_A^{K^*}}{\partial q_A^{T^*}}\right]\frac{\partial q_A^{T^*}}{\partial\gamma}+\frac{\partial^2\pi_A}{\partial N^2}\frac{\partial N^*}{\partial\gamma}=0$$

where

$$\hat{x}=P_A^F(q_A^{H^*})+q_A^{H^*}P_A^{F'}(q_A^{H^*})-C_A(q_A^{H^*}+\delta q_A^{K^*})-(q_A^{H^*}+\delta q_A^{K^*})C_A'(q_A^{H^*}+\delta q_A^{K^*})=0$$

according to Eq. (A3′).

$$\begin{aligned}\hat{y}&=P_A^F(q_A^{K^*})+q_A^{K^*}P_A^{F'}(q_A^{K^*})-\delta C_A\left(q_A^{T^*}+\delta Nq_A^{K^*}\right)-\delta\left(q_A^{T^*}+3\delta Nq_A^{K^*}\right)C_A'\left(q_A^{T^*}+\delta Nq_A^{K^*}\right)-\delta^2N^*q_A^{K^*}(q_A^{T^*}+\delta N^*q_A^{K^*})C_A''\\&\quad-\delta C_A(q_A^{H^*}+\delta q_A^{K^*})-\delta(q_A^{H^*}+\delta q_A^{K^*})C_A'(q_A^{H^*}+\delta q_A^{K^*})-(1-\delta)\left[C_A(q_A^{K^*})+q_A^{H^*}C_A'(q_A^{K^*})\right]\\&=-\delta(q_A^{T^*}+2\delta N^*q_A^{K^*})C_A'(q_A^{T^*}+\delta N^*q_A^{K^*})-\delta^2N^*q_A^{K^*}(q_A^{T^*}+\delta N^*q_A^{K^*})C_A''\end{aligned}$$

according to Eq. (A4′).

Given that $\partial^2\pi_A/\partial N^2\leqslant 0$, we have $\partial N^*/\partial\gamma>0$ as long as

$$2C_A'(q_A^{T^*}+\delta N^*q_A^{K^*})+(q_A^{T^*}+\delta N^*q_A^{K^*})C_A''+\hat{y}\frac{\partial q_A^{K^*}}{\partial q_A^{T^*}}>0$$

According to Lemma 1, $\partial q_A^{K^*}/\partial q_A^{T^*}\leqslant 0$ if

$$2C_A'(q_A^{T^*}+\delta N^*q_A^{K^*})+(q_A^{T^*}+\delta N^*q_A^{K^*})C_A''\geqslant 0$$

In order to get a more clear result, we impose the functional form of $C_A\left(Q_A^I\right)$ and have:

$$2C_A'(q_A^{T^*}+\delta N^*q_A^{K^*})+(q_A^{T^*}+\delta N^*q_A^{K^*})C_A''=-2\beta+3(q_A^{T^*}+\delta N^*q_A^{K^*})\theta$$

$$\begin{aligned}\hat{y}&=-\delta\left[(q_A^{T^*}+2\delta N^*q_A^{K^*})C_A'(q_A^{T^*}+\delta N^*q_A^{K^*})+\delta N^*q_A^{K^*}(q_A^{T^*}+\delta N^*q_A^{K^*})C_A''\right]\\&=-\delta\left[-(q_A^{T^*}+2\delta N^*q_A^{K^*})\beta+(q_A^{T^*}+\delta N^*q_A^{K^*})(q_A^{T^*}+3\delta N^*q_A^{K^*})\theta\right]\end{aligned}$$

It is clear that when $q_A^{T^*}$ or δ is larger, it is more likely for $2C_A'\left(q_A^{T^*}+\delta Nq_A^{K^*}\right)+\left(q_A^{T^*}+\delta Nq_A^{K^*}\right)C_A''>0$ as well as $\hat{y}<0$. In other words, it is more likely that $\partial N^*/\partial\gamma>0$.

Other things equal, the larger the trunk market size is, the larger $q_A^{T^*}$ will be.

On the other hand, the larger θ is, the more likely this result holds, since θ is a multiplicative term to both $q_A^{T^*}$ and δ. □

Proof of Proposition 3. Taking derivative of (A6) with respect to γ, we have

$$-Nq_A^{K^*}\left[2C_A'\left(q_A^{T^*}+\delta^*Nq_A^{K^*}\right)+\left(q_A^{T^*}+\delta^*Nq_A^{K^*}\right)C_A''+\tilde{x}\frac{\partial q_A^{H^*}}{\partial q_A^{T^*}}+\tilde{y}\frac{\partial q_A^{K^*}}{\partial q_A^{T^*}}\right]\frac{\partial q_A^{T^*}}{\partial\gamma}+\frac{\partial^2\pi_A}{\partial\delta^2}\frac{\partial\delta^*}{\partial\gamma}=0$$

where

$$\tilde{x}=-Nq_A^{K^*}\left[2C_A'(q_A^{H^*}+\delta^*q_A^{K^*})+(q_A^{H^*}+\delta^*q_A^{K^*})C_A''\right]>0$$

$$\tilde{y}=-\delta^*N\left[2C_A'\left(q_A^{T^*}+\delta^*Nq_A^{K^*}\right)+\left(q_A^{T^*}+\delta^*Nq_A^{K^*}\right)C_A''\right]-\delta^*\left[2C_A'(q_A^{H^*}+\delta^*q_A^{K^*})+(q_A^{H^*}+\delta^*q_A^{K^*})C_A''\right]+C_A'(q_A^{K^*})$$

Given that $\partial^2\pi_A/\partial\delta^2\leqslant 0$, we have $\partial\delta^*/\partial\gamma>0$ as long as

$$2C_A'\left(q_A^{T^*}+\delta^*Nq_A^{K^*}\right)+\left(q_A^{T^*}+\delta^*Nq_A^{K^*}\right)C_A''+\tilde{x}\frac{\partial q_A^{H^*}}{\partial q_A^{T^*}}+\tilde{y}\frac{\partial q_A^{K^*}}{\partial q_A^{T^*}}>0$$

In order to get a more clear result, we impost the functional form of $C_A(Q_A^I)$ and have:

$$2C'_A\left(q_A^{T^*}+\delta^* N q_A^{K^*}\right)+\left(q_A^{T^*}+\delta^* N q_A^{K^*}\right)C''_A=-2\beta+3\left(q_A^{T^*}+\delta^* N q_A^{K^*}\right)\theta$$

$$\tilde{y}=-\delta^* N\left[-2\beta+3\left(q_A^{T^*}+\delta^* N q_A^{K^*}\right)\theta\right]-\delta^*\left[-2\beta+3(q_A^{H^*}+\delta^* q_A^{K^*})\theta\right]+\left[-\beta+q_A^{K^*}\theta\right]$$

Again, when $q_A^{T^*}$ or N is larger, it is more likely for $2C'_A\left(q_A^{T^*}+\delta^* N q_A^{K^*}\right)+\left(q_A^{T^*}+\delta^* N q_A^{K^*}\right)C'_A$ as well as $\tilde{y}<0$. And it means that it is more likely that $\partial\delta^*/\partial\gamma>0$. The larger the trunk market size is, the larger $q_A^{T^*}$ will be.

On the other hand, the larger θ is, the more likely this result holds, since θ is a multiplicative term to both $q_A^{T^*}$ and N. □

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