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A note on optimal airline networks under airport congestion

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HIGHLIGHTS

- Airport congestion is a severe economic problem.
- We examine optimal airline networks under airport congestion.
- Airlines exhibit a preference for hub-and-spoke (HS) configurations.
- Airlines may be inefficiently biased towards HS networks.
- We recommend regulatory tools like congestion pricing or slot constraints.

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ABSTRACT

We extend the monopoly case without congestion in Brueckner (2004) by examining network choice in a duopoly where airport congestion can occur. Airlines prefer hub-and-spoke configurations, even if this implies higher congestion costs. Airlines may be inefficiently biased towards hub-and-spoke networks.

1. Introduction

The deregulation of air transportation allowed carriers to make strategic choices about fares and networks. The success of hub-and-spoke (HS) structures can be explained in terms of the savings carriers made from operating fewer routes and from exploiting economies of traffic density. However, the concentration of traffic favored by HS networks has contributed to an increase in airport congestion causing delays, cancellations, and missed connections, all of which ends up having a detrimental impact on passengers and airlines alike.

Congestion is a severe problem and it is especially worrisome in HS networks.[1] Since network structure is essential to understand the problem of congestion, our main aim is to examine this relationship and assess the eventual detrimental effects of HS networks on social welfare.

We study network choice in a duopoly with schedule competition where congestion can occur. First, we compare the incentives for airlines to operate either HS or fully-connected (FC) networks.

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[1] On the one hand, the magnitude of the problem can be noticed by looking at data over the period 2005–2013 for the top 50 US airports (data from RDC Aviation, Capstat Statistics), which reveals that the percentage of flights suffering a delay longer than 15 min was about 22%. On the other hand, the relationship between HS networks and congestion is empirically shown in Brueckner (2002), which shows that delays are higher in hub airports after controlling for airport size and other airport attributes.

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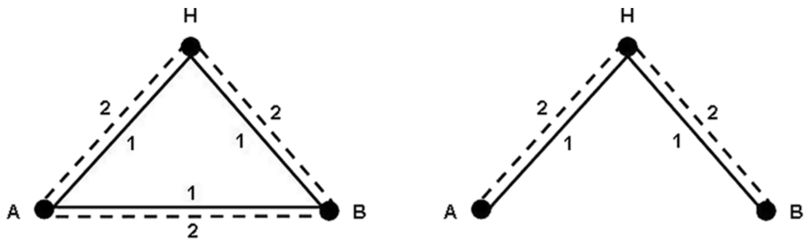

Fig. 1. The FC and HS networks.

We find that airline profits are higher under HS networks without congestion and that this result is typically reinforced in the presence of congestion. Second, we perform a welfare analysis revealing that airlines choose excessive frequencies and that they may be inefficiently biased towards HS networks, especially in a congested environment. Our analysis suggests the need to apply regulatory tools like congestion pricing or slot constraints.

We bring together two strands of the literature: one on airport congestion and another one on airlines' network choice.[2] Brueckner (2004) studies the monopoly case (without congestion) and finds an inefficient bias towards the HS network. He suggests that a model including airline competition should corroborate his result. Our paper fills this gap.

2. Model and equilibrium analysis

We assume the simplest possible network with three cities (A, B, and H), two airlines (1 and 2), and three city-pair markets (AH, BH, and AB). AB can be served either nonstop (FC network) or via hub H (HS network), as shown in Fig. 1.

Passenger population size in each market is normalized to unity and we limit market power by assuming fully-served markets.[3]

The two symmetric networks are compared. Therefore, we do not perform a complete equilibrium analysis since we do not consider the asymmetric case. The reason is twofold: an asymmetric outcome is not likely to arise in equilibrium (with fully-served markets and symmetric carriers),[4] and it would complicate severely the exposition of the results. We are implicitly assuming a coordination game with two symmetric equilibria and our purpose is to develop a focal criterion to select the Pareto-superior equilibrium.

2.1. FC network

Utility for a passenger traveling with carrier 1 is

$$u_1 = \underbrace{y - p_1}_{\text{Consumption}} - \underbrace{\frac{\gamma}{f_1}}_{\text{Expected schedule delay}} - \underbrace{\lambda\,(4f_1 + 4f_2)}_{\text{Congestion damage}} + \underbrace{b + a}_{\text{Travel benefit}}. \quad (1)$$

Consumption equals $y - p_1$, where p_1 is airline 1's fare and y denotes income. The *expected schedule delay* is decreasing with frequency, where $\gamma > 0$ captures the disutility of schedule delay (as Brueckner, 2004). The *congestion damage* depends on the aircraft movements at the origin and destination airports ($2f_1 + 2f_2$ at each airport), where $\lambda \geqslant 0$ captures the disutility of congestion (as Flores-Fillol, 2010). Finally, *travel benefit* includes the gain from travel (b) and the airline brand-loyalty (a),[5] which is uniformly distributed over $[-\alpha/2, \alpha/2]$ and denotes the utility gain from using airline 1 (as Brueckner and Flores-Fillol, 2007). Interestingly, α measures product differentiation.[6] The analysis is presented for carrier 1 (expressions for carrier 2 are derived analogously).

A passenger loyal to 1 (with $a > 0$) will fly with her preferred carrier when $y - p_1 - \gamma/f_1 + b + a > y - p_2 - \gamma/f_2 + b$, i.e., when $a > p_1 - p_2 + \gamma/f_1 - \gamma/f_2 \equiv \widehat{a}$.[7] Then, carrier 1's traffic is

$$q_1 = \int_{\widehat{a}}^{\alpha/2} \frac{1}{\alpha} da = \frac{1}{2} - \frac{1}{\alpha}(p_1 - p_2 + \gamma/f_1 - \gamma/f_2). \quad (2)$$

Carrier 1's total costs on a route are

$$c_1 = f_1 \left[\underbrace{\theta}_{\text{Fixed cost}} + \underbrace{\tau s_1}_{\text{Seat cost}} + \underbrace{\eta\,(4f_1 + 4f_2)}_{\text{Congestion cost}} \right], \quad (3)$$

where τ is the marginal cost per seat, s_1 is carrier 1's aircraft size, and $\eta \geqslant 0$ denotes airlines' congestion damage. As in Brueckner (2004), the cost per seat falls with aircraft size, capturing the presence of economies of traffic density. Frequency, aircraft size, and traffic are related by $s_1 = q_1/f_1$.[8] Therefore (3) can be rewritten as

$$c_1 = \theta f_1 + \tau q_1 + f_1 \eta\,(4f_1 + 4f_2). \quad (4)$$

Airline 1's profit is $\pi_1 = 3\,(p_1 q_1 - c_1)$ and, using (4), it becomes

$$\pi_1 = 3 \left\{ \underbrace{(p_1 - \tau)\, q_1}_{\text{Margin}} - \underbrace{f_1 \left[\theta + 4\eta\,(f_1 + f_2)\right]}_{\text{Congestion and fixed cost}} \right\}. \quad (5)$$

Airlines maximize profits by choosing fares and frequencies. Plugging (2) into (5), $\partial\pi_1/\partial p_1$ and $\partial\pi_1/\partial f_1$ can be computed.[9] From $\partial\pi_1/\partial p_1$, after applying symmetry, we obtain

$$p = \tau + \alpha/2, \quad (6)$$

2 Studies on airport congestion include, among others, Daniel (1995), Brueckner (2002), Daniel and Harback (2008), and Flores-Fillol (2010). The literature on airlines' network choice includes, among others, Pels et al. (2000), Brueckner (2004), and Flores-Fillol (2009).

3 As in Flores-Fillol (2010), market power only affects the division of a fixed traffic pool. Partially-served markets introduce tractability complications since a reduction in frequency mitigates congestion but raises fares.

4 Flores-Fillol (2009) performs a *full* equilibrium analysis in the absence of congestion. Asymmetric networks only occur in equilibrium when markets are partially served.

5 Without brand loyalty, the airline with the most attractive frequency/fare combination would attract all the passengers.

6 A small (large) α indicates similar (different) products, i.e., a small (large) gain from using an airline.

7 Analogously, the utility of a passenger traveling with carrier 2 is $u_2 = y - p_2 - \frac{\gamma}{f_2} - \lambda\,(4f_1 + 4f_2) + b - a$, with $a < 0$ for passengers loyal to carrier 2 and $a > 0$ for passengers loyal to carrier 1.

8 As such, we assume that all seats are filled. In Fageda and Flores-Fillol (2012), the 100% load factor assumption is relaxed. This distinction is not needed for the purposes of this analysis and, in any case, high load factors are a prerequisite for profitability.

9 $\partial^2\pi_1/\partial p_1^2$ and $\partial^2\pi_1/\partial f_1^2 < 0$ are satisfied by inspection. The positivity condition on the Hessian determinant, which is assumed to hold, requires $p_1 - \tau > \frac{\gamma}{4f_1} - \frac{4\alpha\eta f_1^3}{\gamma}$, i.e., margins have to be sufficiently large.

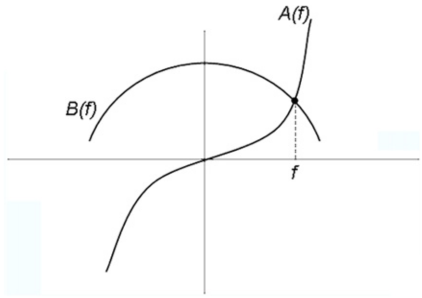

Fig. 2. The f solution.

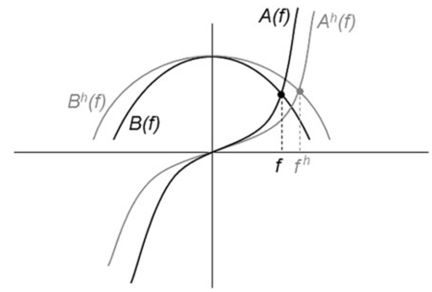

Fig. 3. Comparing f and f^h.

revealing that the fare equals the marginal cost plus a markup. As differentiation disappears, the fare converges to the marginal cost (Bertrand equilibrium). Using (6), $\partial\pi_1/\partial f_1$ yields

$$\underbrace{12\eta f^3}_{A(f)} = \underbrace{\frac{\gamma}{2} - \theta f^2}_{B(f)}. \tag{7}$$

The equilibrium frequency is found graphically in Fig. 2, at the intersection between a cubic and a quadratic expression.[10]

2.2. HS network

The HS case coincides with the base case in Flores-Fillol (2010). As compared to the FC case, the route AB is eliminated and AB passengers change planes at the hub. Thus, airline 1 maximizes

$$\pi_1^h = \underbrace{2\left(p_1^h - \tau\right) q_1^h}_{\text{Local margin}} + \underbrace{\left(P_1^h - 2\tau\right) Q_1^h}_{\text{Connecting margin}} - \underbrace{2f_1^h \left[\theta + 3\eta\left(f_1^h + f_2^h\right)\right]}_{\text{Congestion and fixed cost}}, \tag{8}$$

where superscript h denotes HS and P_i^h and Q_1^h are fares and traffic in market AB. Airline's congestion cost on a route is given by $\eta\left(3f_1^h + 3f_2^h\right)$ because congestion on a route is caused by aircraft movements both at the hub $(2f_1^h + 2f_2^h)$ and at the spoke airport $(f_1^h + f_2^h)$. Profit maximization yields

$$p^h = \tau + \alpha/2 \quad \text{and} \quad P^h = 2\tau + \alpha/2. \tag{9}$$

The connecting fare takes now into account the fact that two routes are needed to serve this market. The condition for frequency is

$$\underbrace{6\eta\left(f^h\right)^3}_{A^h(f)} = \underbrace{\frac{\gamma}{2} - \frac{2\theta}{3}\left(f^h\right)^2}_{B^h(f)}, \tag{10}$$

and the equilibrium is generated by a diagram analogous to Fig. 2.

2.3. Comparison of frequencies and profits

Equilibrium frequencies are compared in Fig. 3, using (7) and (10).

The f^2-coefficient and the height of the cubic curve in the positive quadrant are greater in the FC case.

Proposition 1. *Frequency is higher in HS networks: $f^h > f$.*

Frequency is higher under HS networks because there is more traffic on each of the two active routes. This finding extends the result in Flores-Fillol (2009) to a setting with congestion.

The total number of flights operated by an airline under FC networks is $3f$ since three routes are active. Analogously, an airline under HS networks operates $2f^h$ flights.

Assumption 1. HS operations reduce the number of flights: $2f^h < 3f$.

As pointed out in Brueckner (2004), this seems a natural expectation since HS networks are meant to cut airline costs by operating fewer routes. $s < s^h$ is observed under Assumption 1, a realistic implication that is in line with Brueckner (2004) and Flores-Fillol (2009).[11] HS configurations provide the passengers with higher frequency and allow airlines to make cost savings due to the presence of economies of traffic density as the aircraft size can be larger.

Comparing equilibrium profits is not trivial because the closed-form solution for frequency is complex. However, this comparison can be completed by recasting the optimization as a two-stage problem, where fares are first chosen conditional on frequency, and frequency is then chosen.

Substituting (6) into (5) and applying symmetry, we obtain

$$\pi_1(f) = \frac{3\alpha}{4} - 3\theta f - 24\eta f^2, \tag{11}$$

where the first factor 3 denotes the number of markets served; the second factor 3 indicates the number of routes operated; and the factor 24 shows that each of the routes is affected by eight aircraft movements.

Substituting (9) into (8) and applying symmetry, we obtain

$$\pi_1^h\left(f^h\right) = \frac{3\alpha}{4} - 2\theta f^h - 12\eta\left(f^h\right)^2, \tag{12}$$

where factors 3 and 2 denote that the airline serves three markets but only two routes; and the factor 12 shows that each of the routes is affected by six aircraft movements.

Using (11) and (12), the HS–FC profit differential yields

$$\begin{aligned}\Delta &= \pi_1^h\left(f^h\right) - \pi_1(f) \\ &= \underbrace{\theta\left(3f - 2f^h\right)}_{>0\ (\text{HS advantage})} + \underbrace{12\eta\left[2f^2 - \left(f^h\right)^2\right]}_{\substack{>0 \text{ for } f^h < 1.4f\ (\text{HS advantage}) \\ <0 \text{ for } f^h > 1.4f\ (\text{HS disadvantage})}}.\end{aligned} \tag{13}$$

The first term is positive and captures the aircraft's fixed cost advantage of HS networks from operating only two routes. The second term can be positive or negative and captures the congestion cost advantage that can favor either network structure.

Proposition 2. *Without congestion ($\lambda = \eta = 0$), airline profits are higher under HS networks. In the presence of congestion, airline profits are higher under HS networks when $f^h \leqslant 1.4f$.*

The sign of Δ is unclear for $f^h > 1.4f$. Corollary 1 analyzes the effect of congestion on Δ.

[10] A comparative-static analysis can be done from (7) and Fig. 2. More information available on request.

[11] In equilibrium, aircraft size under each network type is $s_1 = q_1/f = 1/(2f)$ and $s_1^h = \left(q_1^h + Q_1^h\right)/f_1^h = 1/f^h$.

Corollary 1. *Congestion increases the profitability of HS networks* ($\partial\Delta/\partial\eta > 0$) *for* $f^h < 1.4f$ *and decreases the profitability of HS networks* ($\partial\Delta/\partial\eta < 0$) *for* $1.4f < f^h < 3f/2$.

Congestion creates incentives for airlines to adopt HS networks, except for $1.4f < f^h < 3f/2$. When f^h is very high and falls within this interval, the sign of Δ is ambiguous and congestion acts as a brake on hubbing strategies.

3. Welfare analysis

We now shift our attention to the welfare analysis where a social planner dictates frequency. Then we assess airlines' incentives to operate either network configuration.

3.1. Frequency choice

First, we focus on the FC setting. Since fares are transfers between consumers and airlines and markets are fully served, the planner's goal is to minimize costs, which are

$$3\left\{\underbrace{\frac{1}{2}\left(\frac{\gamma}{f_1}+\frac{\gamma}{f_2}\right)}_{\text{Schedule delay cost}}+\underbrace{4\lambda\,(f_1+f_2)}_{\text{Congestion cost for passengers}}\right.$$
$$\left.+\underbrace{(f_1+f_2)\left[\theta+\eta(4f_1+4f_2)\right]}_{\text{Fixed and congestion cost for airlines}}+\underbrace{\tau}_{\text{Seat cost}}\right\}. \tag{14}$$

On the passengers side, the *schedule delay cost* caused by each airline acquires a $3/2$ factor because there are three markets and half of the unitary population in each market is loyal to each airline. The *congestion cost for passengers* has a 12 factor that accounts for aircraft movements in the three markets. On the airline side, each carrier bears the *fixed and congestion cost* of operating three routes and the *seat cost* of serving three markets.

We compute the optimal choice of f_1 and then we apply symmetry, which yields

$$\underbrace{16\eta f^3}_{C(f)}=\underbrace{\frac{\gamma}{2}-(\theta+4\lambda)f^2}_{D(f)}. \tag{15}$$

(7) and (15) are compared in Fig. 4. The social-optimum cubic function is higher and the social-optimum f^2-coefficient is larger for $\lambda > 0$.

The equilibrium frequency is excessive and the aircraft size is inefficiently small. The inefficiency disappears in the absence of congestion.

The HS cost expression is

$$\underbrace{\frac{3}{2}\left(\frac{\gamma}{f_1^h}+\frac{\gamma}{f_2^h}\right)}_{\text{Schedule delay cost}}+\underbrace{10\lambda\left(f_1^h+f_2^h\right)}_{\text{Congestion cost for passengers}}+\underbrace{\mu}_{\text{Layover time cost}}$$
$$+\underbrace{2(f_1^h+f_2^h)\left[\theta+\eta(3f_1^h+3f_2^h)\right]}_{\text{Fixed and congestion cost for airlines}}+\underbrace{4\tau}_{\text{Seat cost}}. \tag{16}$$

The *congestion cost for passengers* has a factor 10 that accounts for all aircraft movements (three corresponding to *AH* and *BH*, and four corresponding to *AB*), and there is the *layover time cost* borne by connecting passengers. Each carrier bears the *fixed cost and congestion cost* of operating two routes and the *seat cost*, which acquires a factor 4 because it accounts for local passengers (who travel on one route) and connecting passengers (who travel on two routes).

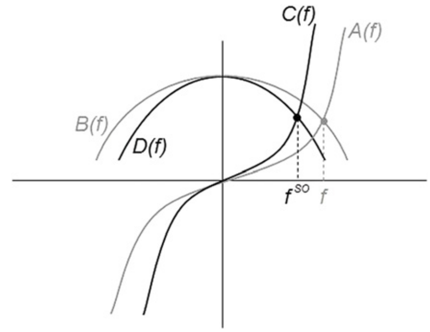

Fig. 4. Overprovision of frequency.

We compute the optimal choice of f_1^h and then we apply symmetry, which yields

$$\underbrace{8\eta\left(f^h\right)^3}_{C^h(f)}=\underbrace{\frac{\gamma}{2}-\frac{2(\theta+5\lambda)}{3}\left(f^h\right)^2}_{D^h(f)}. \tag{17}$$

(10) and (17) can be represented by a diagram analogous to Fig. 4, where we observe that congestion makes airlines operate too many flights using overly small aircraft.

Proposition 3. *Under each network type, there is an overprovision of frequency and aircraft size is suboptimal. Without congestion, frequency and aircraft size are efficient.*

3.2. Network efficiency

Using (16) and (14), the HS–FC welfare differential yields

$$\Gamma = W^h - W = 2\Delta + k, \quad \text{with} \tag{18}$$
$$k=\underbrace{3\gamma\left(1/f-1/f^h\right)}_{>0\ (\text{HS advantage})}\ \underbrace{-(\tau+\mu)}_{<0\ (\text{HS disadvantage})}+\underbrace{4\lambda\left(6f-5f^h\right)}_{\substack{>0 \text{ for } f^h<1.2f\,(\text{extra HS advantage})\\ <0 \text{ for } f^h>1.2f\,(\text{extra HS disadvantage})}}.$$

There is a *HS advantage* in schedule delay given that HS structures yield a larger frequency (see Proposition 1). However, there is also a *HS disadvantage* associated to carrying connecting passengers: an extra seat and a layover time cost because these passengers make use of two routes and change planes at the hub. Finally, the different impact of HS and FC networks on passenger congestion costs can constitute an *extra HS advantage* or *disadvantage*. The sign of this effect depends on the relative value of f^h and f because, as f^h rises, there is an increase in the probability of delays at the hub.

With $k = 0$, the sign of Γ and Δ coincides and the airlines' preferred network is efficient. However, with $k \neq 0$, airlines' choices may be inefficient. Without congestion ($\lambda = \eta = 0$), $\Delta > 0$ and a conflict between private and public interests can arise when $k < 0$ (i.e., $3\gamma\left(1/f - 1/f^h\right) < \tau + \mu$), which means that the *HS disadvantage* exceeds the *HS advantage*.

In the presence of congestion, studying the sign of Γ requires to analyze Δ and k simultaneously:

- When $f^h \leqslant 1.4f$, then $\Delta > 0$ and a private–public conflict can arise again when $k < 0$ (i.e., $3\gamma(1/f - 1/f^h) + \underbrace{4\lambda(6f - 5f^h)}_{\substack{>0 \text{ for } f^h<1.2f\\ <0 \text{ for } f^h>1.2f}} < \tau + \mu$).

- When $f^h > 1.4f$, the sign of Δ is ambiguous and airlines' choice may exhibit an inefficient bias either towards HS or FC networks.[12]

Proposition 4. *Without congestion, airlines' network choice exhibits an inefficient bias towards HS networks when the HS disadvantage associated to carrying connecting passengers exceeds the HS advantage in terms of schedule delay. In the presence of congestion, this result holds for* $f^h \leqslant 1.4f$.

Congestion typically exacerbates this inefficiency. Corollary 1 showed that congestion increases the HS profitability for $f^h < 1.4f$ and, as explained in Proposition 4, this yields an inefficient bias towards HS networks. This result is reinforced for $f^h \in (1.2f, 1.4f]$ because there is an *extra HS disadvantage*.

Brueckner (2004) studies the monopoly case (without congestion) and finds an inefficient bias towards HS networks for $f^h < 3f/2$. He suggests that a model including airline competition should corroborate his result. We extend and complement his analysis.

4. Policy implications

Carriers could have incentives to operate HS networks, ignoring the derived social costs in terms of congestion. Our results suggest that policy measures promoting direct connections may have social benefits. Policy makers and airport operators could use such tools as congestion tolls, capacity investment, and a better marketing of the cities in which non-hub airports are located. The rules determining the allocation and use of slots could also be re-designed so as to create incentives for airlines to increase aircraft size and reduce their frequency.

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12 In a highly congested environment where both η and λ are large, then $\Delta < 0$ and $k < 0$ (i.e., $3\gamma(1/f - 1/f^h) + \underbrace{4\lambda(6f - 5f^h)}_{<0} < \tau + \mu$), so that there is no private–public conflict and the FC network is preferred. However, if θ is sufficiently high as compared to η, then $\Delta > 0$ and $k < 0$ could be observed, yielding an inefficient bias towards HS networks.