Airline network rivalry

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Abstract. In this paper the effects of the strategic interaction between deregulated airlines on their network choice are analysed. We examine whether switching from a linear to a hub-spoke network confers a strategic advantage because it saves costs and improves service quality. We find that if hubbing lowers total cost (which includes both airline and passenger inconvenience costs), the pursuit of strategic advantages usually intensifies the extent of hubbing. Even if hubbing raises total cost, it might be pursued by the airline, either because hubbing is a dominant strategy in an oligopolistic setting or because hubbing will be useful in deterring entry.

Rivalité dans un réseau aérien. Ce mémoire analyse les effets de l'interaction stratégique entre compagnies aériennes en régime de dérèglementation sur leur choix de réseau. On se demande si la décision de se déplacer d'un réseau linéaire vers un réseau en roue (hub-spoke) confère un avantage stratégique parce que cela réduit les coûts et accroît la qualité. On découvre que si le réseau en roue réduit le coût total (les coûts de contretemps de toutes sortes tant des compagnies que des usagers), la poursuite d'avantages stratégiques entraine l'intensification du processus de passage au réseau en roue. Même si ce processus augmente les coûts totaux, il se peut que la compagnie aérienne poursuive quand même cette stratégie soit parce que c'est une stratégie dominante dans un contexte oligopolistique soit parce que ce processus est un instrument utile pour décourager l'entrée dans l'industrie.

I. INTRODUCTION

A striking feature of deregulated airline markets has been the near-universal adop-

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tion of a 'hub-spoke' form of airline route structure. Hub-spoke networks concentrate most of an airline's operations at one, or a very few, hub cities. Virtually all other cities in the network are served by non-stop flights from these hubs. In such a network, travellers between cities on the spokes catch connecting flights at the hub city. Originally, when the airline industry was regulated, U.S. and Canadian carriers were constrained in their choice of routes and, as a result, airline routes did not converge excessively at any particular cities. The pre-deregulation route structure is sometimes referred to as a linear network, reflecting the tendency of the regulatory bodies to authorize airlines to provide direct services between two specific points.[1]

It appears that a hub-spoke network provides important advantages to its operator in the production and marketing of air travel services. On the production side, hubbing reduces costs by taking advantage of the economies of route traffic density. These economies arise from a reduction in the cost per passenger on a given route as the number of passengers travelling on the route rises (e.g., Caves, Christensen, and Tretheway 1984). By routing passengers through a hub, an airline is able to achieve a higher traffic density than would be possible under a linear route structure. On the marketing side, routing flights through a hub facilitates more frequent departures to a large number of cities, thereby making services more attractive to travellers.

The value of hub-spoke networks for cost saving and marketing advantages was recognized before deregulation. Few economists, however, predicted the thoroughgoing movement to hub-spoke operations and the value of the market power that operators could derive from their hubs. The dominance of hub-spoke networks has recently raised some concerns that such systems may provide a barrier to new entry, thereby reinforcing the market power of the dominant carriers at the hub. Borenstein (1989), Berry (1990), and Evans and Kessides (1993a) investigated empirically the relationships between hub-spoke route structures and market power. They found strong evidence that an airline's domination of a hub results in higher fares for routes to and from that hub. Consumers may be willing to pay a price premium for the services of dominant airlines because of factors such as flight frequency, consumers' search efforts, and frequent-flyer programs. It also suggests the importance of understanding the strategic interaction between airlines so as to explain their post-deregulation network strategies.

In this paper we attempt to analyse the effects of the strategic interaction between deregulated airlines on their network choice. Two route structures are considered: a linear system, under which city-pair markets are served via non-stop flights, and a hub-spoke system, under which passengers between cities on the spokes must take connecting flights at the hub. We examine whether switching from a linear

1 McShane and Windle (1989) provide a measure of the increase in hubbing after deregulation. They show that the total departures of each carrier became increasingly concentrated at selected airports (the carrier's hubs): for a typical U.S. carrier, the percentage of departures leaving its hubs increased from 24 per cent in 1977 to 39 per cent in 1984. Similar data are provided by Bailey, Graham, and Kaplan (1985).

to a hub-spoke network confers a strategic advantage because it saves costs and improves service quality.

Our second objective is to develop a methodology that can be applied to the analysis of multiproduct oligopolistic competition with network-oriented firms. In our analysis, an airline is a multiproduct firm, with each of its products corresponding to travel in a particular origin-destination city-pair market. Further, each carrier is a network-oriented firm in the sense that the network type will affect the nature of interaction among its different products. Specifically, we identify a 'network effect' under a hub-spoke system: the marginal profit of a carrier's local output increases in its connecting output and vice versa. This network effect, which is absent under a linear system, arises for two reasons. As route traffic density increases, there is (i) a reduction in marginal costs; and/or (ii) an improvement in service quality, owing to an increase in flight frequency. The cost-based network effect has been identified in earlier theoretical papers (Brueckner and Spiller 1991; Bittlingmayer 1990).[2] A major contribution of this paper is the identification and analysis of the type-(ii) network externality and an analysis of how it operates as a strategic instrument.

Because network structures influence specification of the profit function, and hence the output market equilibrium, carriers with foresight will have an incentive to choose a network structure to influence the output rivalry in their favour. We show that by committing its products to the hub-spoke network, a carrier can enjoy a strategic advantage conferred by the network effect. Essentially, with the network effect, hubbing allows the carrier to commit to a higher level of outputs, since it lowers marginal cost and/or raises marginal revenue. This causes own outputs to rise and induces the rivals' outputs to fall. The pursuit of this strategic advantage by airlines will usually strengthen the need to use a hub-spoke system, as opposed to a linear system. We identify conditions under which hubbing is a dominant strategy in an oligopolistic setting and further demonstrate that an incumbent airline might use hubbing as a device to deter entry.

The basic analytical results of the paper and the intuition for them are similar to the two-stage games in industrial organization in which current actions alter the subsequent competitive environment (see Shapiro 1989 for a comprehensive survey). More specifically, we shall establish our network game as one of the strategic substitutes games in which investment in hubbing makes a firm 'tough' in product market competition; thus, hubbing is a 'top-dog' strategy in the terminology of Fudenberg and Tirole (1984). However, most of the work in the two-stage competition literature focuses on the case of one product per firm. An innovation of this paper is the methodology developed to deal with *multiproduct* oligopoly with network-oriented firms. A valuable study on multiproduct oligopoly is Brander and Eaton (1984), who examined product line choices for multiproduct firms. Our paper is in a similar vein but is concerned primarily with airline network rivalry,

2 The external effect within hub-spoke networks is tested empirically in Brueckner, Dyer, and Spiller (1992), which demonstrates that the cost-reducing effect of networks indeed shows up in airfares.

in which the product line is fixed for each firm but the network type affects the nature of interaction among the products within the line.[3]

Various researchers have offered explanations for the dramatic growth of hub-spoke systems under deregulation. Levine (1987) and Oum and Tretheway (1990) concluded that the current dominance of hub-spoke networks is the result of airlines' exploiting economies of traffic density and strategic advantages which could not be pursued under regulation. Berry (1990) provided some empirical evidence that both cost efficiency and market power lead to airport dominance; McShane and Windle (1989) quantified the (positive) effect of hubbing on cost efficiency. Hendricks, Piccione, and Tan (1995) used a monopoly structure to formalize the idea that economies of density may be an important reason for the emergence of hub-spoke systems. However, the exact mechanism by which the strategic interaction between airlines influences their network choice has not yet been formally established in the literature. This paper attempts to provide an analysis of one such mechanism.[4]

In section II we set out the basic model. In section III we briefly consider the network choice for a monopoly firm, and in section IV the main results on airline network rivalry are derived. The use of hub-spoke networks as a device for entry deterrence are examined in section V, and we present concluding remarks in section VI.

II. THE MODEL

We shall consider an air transport system that is likely the simplest structure in which our questions can be addessed. There are three cities: H, I, and J in this system (figure 1). The three city-pair markets, IH, JH, and IJ, in which passengers originate in one city and terminate in the other, are labelled 1, 2, and 3, respectively. We assume that only H can be developed as a hub. If a carrier serves all three markets and uses H as its hub, it will provide connecting flights between I and J through H; as a result, its aircraft are flown only on the IH and JH routes (represented by the solid lines in figure 1a). Such a route structure is referred to as a 'hub-spoke network.' Note that on a given spoke, say, IH, aircraft carry both local (i.e., H to I) passengers and connecting (i.e., J to I) passengers (traffic also includes passengers returning from I to H and J). A carrier that serves all three markets, however, may choose not to hub. In that case, it would offer non-stop flights in the IJ market, and consequently its aircraft are flown on all three routes. We refer to this route structure as a 'linear network' (figure 1b).

3 Useful studies on some different aspects of multiproduct oligopoly include Bulow, Geanakoplos and Klemperer (1985), Judd (1985), Whinston (1990), Klemperer (1992), and Gilbert and Matutes (1993).

4 Researchers have also studied the impacts of hub-spoke systems on, among other things, airport planning and operation (Kanafani and Ghobrial 1985), the susceptibility of a monopoly market to entry (Bittlingmayer 1990), and antitrust policy (Brueckner and Spiller 1991; Zhang and Wei 1993; Kahn 1993). Other useful references on deregulated airline markets include Bailey et al. (1985), Keeler (1991), Tretheway and Oum (1992), Borenstein (1992), and Evans and Kessides (1993b).

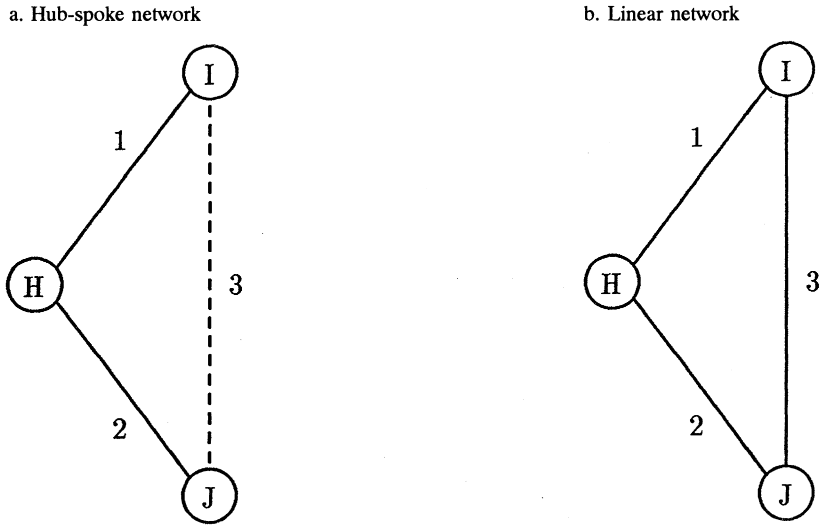

FIGURE 1 A simple air transport system

There are two air carriers ($i = A, B$) serving the transport system. To focus on the network choice, we first assume that the two carriers will enter all three markets and ignore, without loss of generality, the cost associated with entry. (We shall provide discussions on a firm's entry decision in section v.) Our basic model is a two-stage networking game between the two carriers.[5] In stage 1, firms simultaneously select their route structures, either a linear network or a hub-spoke network. If a firm chooses a hub-spoke network, it incurs sunk investment costs of hub development, denoted c_d^i. In stage 2, given the network decision, firms simultaneously establish their output levels for city-pair markets.[6] Note that in this model the network decision is treated as strictly prior to the output decision. As discussed in Levine (1987) and Butler and Huston (1989), hub development requires non-trivial sunk investments: firm- and transaction-specific investments in advertising and initial operations, facilities investments to assemble sufficient gates and landing slots, and others. The lack of space at some of the largest and most centrally located airports makes new hub entry even more costly. As a result, the network structure, once decided upon, cannot easily be altered in a major way. The choice of airline route

5 In this model, we have implicitly assumed that the location of the hub is fixed at H. This assumption allows the effects of the strategic interaction on airlines' network choice to be demonstrated as clearly as possible. One way to let the airlines choose which city to hub is to modify the first-stage game as follows: firms simultaneously select their route structures, either a linear or a hub-spoke network; if a firm chooses a hub-spoke network, it must decide which city to hub and must incur sunk investment costs c_d^i. This extension will add complexity to the analysis and will not alter the basic results of the paper.

6 We assume a Cournot game in the second-stage competition. Brander and Zhang (1990, 1993) and Oum, Zhang, and Zhang (1993) find some empirical evidence that rivalry between duopoly airlines is consistent with Cournot behaviour.

structures is a strategic decision, which might reasonably be regarded as given at the time that competing carriers establish quantities for particular city-pair markets.

Irrespective of its choice of networks, each carrier in question can be viewed as a multiproduct (three-product) firm with a product corresponding to travel in a particular city-pair market. The nature of interaction among a carrier's products, however, depends on its network choice. To show this relationship, we examine the interaction in both demands and costs. Consider costs first. A point-to-point airline incurs production cost $\sum_{k=1}^{3} c_k^i(x_k^i)$, where x_k^i denotes i's output on the kth route and $c_k^i(x_k^i)$ gives the (round-trip) cost of carrying x_k^i passengers on that route. A hub-spoke airline, on the other hand, incurs $\sum_{k=1}^{2} c_k^i(X_k^i) + c_h^i$, with $X_k^i \equiv x_k^i + x_3^i$ and $c_h^i \equiv c_d^i + c_a^i$, where c_a^i denotes some additional costs incurred by routing flights between two spoke cities through the hub. It is noted that X_1^i and X_2^i include both local and connecting passengers and thus refer to the *total* passengers carried by the airline on the spoke routes.

Hubbing also has important implications for the demands for different products. The high traffic densities of a hub-spoke network permit an airline to offer more frequent service on the spoke routes. This in turn will allow the airline to attract more travellers because of the scheduling flexibility. For example, Morrison and Winston (1986, 17) reported, using U.S. data, that a doubling of the frequency of air service would lead to a 21 per cent increase in the demand for air service by business travellers and a 5 per cent increase by leisure travellers. To incorporate the effect of hubbing on demands, one may use the full price demand model (De Vany 1974; Panzar 1979). More specifically, the carriers' demands in the kth market may be written as

$$x_k^A = D_k^A(\rho_k^A, \rho_k^B), \qquad x_k^B = D_k^B(\rho_k^A, \rho_k^B) \tag{1}$$

for $k = 1, 2, 3$, where ρ_k^i is the 'full price' of using carrier i's service. The full price is taken to be the sum of the ticket price, p_k^i, and the 'cost' associated with the quality of i's service. (We assume, as is common in the literature, that consumers are able to place a dollar value on non-price service attributes.) Solving equations (1) for ρ_k^A and ρ_k^B, we obtain the corresponding 'inverse demand' functions (d_k^A and d_k^B are the inverse functions of D_k^A and D_k^B),

$$\rho_k^A = d_k^A(x_k^A, x_k^B), \qquad \rho_k^B = d_k^B(x_k^A, x_k^B). \tag{2}$$

We assume that in each city-pair market the firms' products may but need not be perfect substitutes:[7]

$$\frac{\partial d_k^i}{\partial x_k^j} < 0, \qquad k = 1, 2, 3. \tag{3}$$

7 Here, and below, if the indices i and j appear in the same expression, then it is to be understood that $i \neq j$.

An important aspect of service quality is the passenger's 'schedule delay time,' the time between the passenger's desired departure and the actual departure time. Research has found that the schedule delay associated with a carrier depends largely on the carrier's flight frequency,[8] which in turn depends on its traffic volume on the route. Thus, if Q represented the total passengers carried by i on route k, then the schedule delay cost may be written as $g_k^i(Q)$. It is reasonable to assume that $g'(\cdot) < 0$; that is, the schedule delay cost of an airline falls as its traffic on the route increases.[9]

The passenger delay costs of an airline will vary with the type of network the airline adopts. Under a linear network, the delay cost in each market is given by $g_k^i(x_k^i)$. If the airline adopts a hub-spoke network, however, the delay costs on the two spokes become $g_1^i(X_1^i)$ and $g_2^i(X_2^i)$, whereas the delay cost in the connecting market is the sum of the delay costs on the two spokes, $g_1^i(X_1^i) + g_2^i(X_2^i)$, reflecting the fact that connecting passengers have to travel two connections to reach their final destination. Moreover, owing to the additional descent and ascent at the hub and to extra cruise time required for the circuitous routing, a connecting passenger may suffer an extra cost by flying with a hub-spoke airline compared with non-stop service. Using γ^i to denote this extra cost, the full prices thus can be written as

$$\rho_k^{iL} = p_k^{iL} + g_k^i(x_k^i), \qquad k = 1, 2, 3 \tag{4}$$

under a linear network (L for linear networking), and

$$\rho_1^{iH} = p_1^{iH} + g_1^i(X_1^i), \qquad \rho_2^{iH} = p_2^{iH} + g_2^i(X_2^i),$$
$$\rho_3^{iH} = p_3^{iH} + g_1^i(X_1^i) + g_2^i(X_2^i) + \gamma^i \tag{5}$$

under a hub-spoke network (H for hubbing). According to the full prices specification, the willingness to pay of consumers is the same for the output of each firm and is reduced by the costs of delay and inconvenience.

Given these demand and cost specifications, our two network strategies will give rise to different relationships among products in a firm's profit function. If firm i chooses a linear network, its profit function can be written as, using (2) and (4),

$$\pi^{iL}(x^A, x^B) = \sum_{k=1}^{3} d_k^i(x_k^A, x_k^B)x_k^i - \sum_{k=1}^{3} c_k^i(x_k^i) - \sum_{k=1}^{3} g_k^i(x_k^i)x_k^i, \tag{6}$$

where $x^i \equiv (x_1^i, x_2^i, x_3^i)$ is i's output vector. It can be easily verified that $\partial^2\pi^{iL}/\partial x_k^i \partial x_l^i = 0$ for $k \neq l$. Consequently, the three products (markets) are 'independent' in the sense that the output level in one market will not affect the firm's

8 According to Douglas and Miller (1974), the schedule delay may be decomposed into 'frequency delay' and 'stochastic delay.' The former refers to the difference between one's desired departure time and the closest scheduled departure by the airline, whereas the latter is the delay caused by excess demand for one's preferred flight(s). Both delays are dependent on flight frequency.

9 This condition is quite natural; it holds, for instance, if the schedule delay falls as flight frequency rises and frequency is directly related to traffic volume.

marginal profit in any other market. If i chooses a hub-spoke network, however, its profit can be expressed as, using (2) and (5),

$$\pi^{iH}(x^A, x^B) = \sum_{k=1}^{3} d_k^i(x_k^A, x_k^B)x_k^i - \sum_{k=1}^{2} c_k^i(X_k^i) - c_h^i - \sum_{k=1}^{2} g_k^i(X_k^i)X_k^i - \gamma^i x_3^i. \qquad (7)$$

It is a straightfoward matter to show that $\partial^2\pi^{iH}/\partial x_1^i \partial x_2^i = 0$ and

$$\frac{\partial^2 \pi^{iH}}{\partial x_k^i \partial x_3^i} = -c_k^{i\prime\prime}(X_k^i) + [-2g_k^{i\prime}(X_k^i) - X_k^i g_k^{i\prime\prime}(X_k^i)], \qquad k = 1, 2. \qquad (8)$$

Recall that $c(Q)$ gives the cost of carrying Q passengers on a route. This route cost function is assumed to satisfy the economies of traffic density: the unit cost, $c(Q)/Q$, declines with Q. Since route-specific total cost can be separated into variable costs and fixed costs (airline counters, mechanics, ticket officies, advertising, etc.), the economies can come from two sources: falling marginal costs and spreading fixed costs over more traffic. In the case of falling marginal costs, the first term on the right-hand side of (8) is positive. The second term is also positive, owing to the effect of traffic volumes on schedule delay costs, so the bracketed term will be positive if g is a linear function. More generally, we assume that

$$\frac{\partial^2 \pi^{iH}}{\partial x_k^i \partial x_3^i} > 0, \qquad k = 1, 2. \qquad (9)$$

Condition (9) says that under a hub-spoke network, a carrier's marginal profit of local output increases in its connecting output and vice versa, implying complementarities between local and connecting services. As (8) indicates, these network effects can arise owing to either returns to scale on the production side or network service externalities on the demand side. Specifically, if increased traffic volume allows the carrier to raise the load factor of any scheduled flight, then declining unit costs from greater aircraft seat utilization may give $c'' < 0$.[10] Alternatively, if increased traffic volume allows the carrier to increase flight frequency, then improved convenience will induce more demand, making $-2g' - Xg'' > 0$. Either of these two effects will lead to condition (9).[11] The first effect, the production side complementarities, has been widely recognized in the literature; we emphasize, however, that

10 The network effect of hubbing has been discussed in Brueckner and Spiller (1991) based on declining marginal cost of production: $c'' < 0$.

11 There may be a third factor contributing to this network effect, namely, the increased aircraft size afforded by increased traffic volume on a given route. A fundamental aspect of engineering technology is the decline in cost per seat as aircraft size increases. As discussed in Hendricks et al. (1995), the economics of aircraft size would suggest that falling marginal cost is likely for traffic densities that require only one airplane. This aircraft technology is, in fact, essential for (9) to hold and for the emergence of hub-spoke networks. If it were possible to operate economically with single-seat aircraft, then all passengers could be served directly between their points of origin and destination and at the desired time. There would be no schedule delay and no need for passengers to transfer, and the phenomenon of hubbing would not arise.

even if $c'' = 0$, the externalities can still arise because of demand considerations. In effect, the bracketed term in (8) is positive over a range of plausible schedule delay specifications.[12]

Our goal is to explore the implications of the cross-product (cross-market) relationships in (9) for airline network strategies in an oligopolistic environment. In (3) we have assumed that the outputs of the two firms are substitutes in each city-pair market. Following the standard practice in models of quantity competition (see Dixit 1986; Shapiro 1989), we further assume that in each market a firm's marginal revenue declines when the output of the other firm rises:

$$\frac{\partial^2 \pi^i}{\partial x_k^i \partial x_k^j} < 0, \qquad k = 1, 2, 3. \tag{10}$$

Condition (10) implies that in each market the outputs of the duopolists are 'strategic substitutes' (Bulow et al. 1985).

As a useful analytical tool we introduce the following function:

$$\pi^i(x^A, x^B; \theta^i) \equiv \theta^i \pi^{iH}(x^A, x^B) + (1 - \theta^i)\pi^{iL}(x^A, x^B). \tag{11}$$

Clearly, $\theta^i = 0$ and 1 correspond to a linear and a hub-spoke network, respectively. Letting

$$C^{iH}(x^i) \equiv [c_1^i(X_1^i) + c_2^i(X_2^i) + c_h^i] + [g_1^i(X_1^i)X_1^i + g_2^i(X_2^i)X_2^i + \gamma^i x_3^i] \tag{12}$$

$$C^{iL}(x^i) \equiv [c_1^i(x_1^i) + c_2^i(x_2^i) + c_3^i(x_3^i)] + [g_1^i(x_1^i)x_1^i + g_2^i(x_2^i)x_2^i + g_3^i(x_3^i)x_3^i] \tag{13}$$

and letting $C^i(x^i; \theta^i) \equiv \theta^i C^{iH}(x^i) + (1 - \theta^i)C^{iL}(x^i)$, then (11) can be written as

$$\pi^i(x^A, x^B; \theta^i) = \sum_{k=1}^{3} d_k^i(x_k^A, x_k^B)x_k^i - C^i(x^i; \theta^i). \tag{14}$$

Technically, this equation is equivalent to a profit function with d_k^i as the normal inverse demand function in a duopoly market and C^i as the total 'cost' function for a multi-output producer. It is noted that there are two distinct components in C^i (see (12), (13)): the usual production costs and the costs to passengers resulting from inconvenience of travel. For expositional convenience however, in what follows we shall refer to C^i simply as (total) costs and c^i as production costs.

12 This can be seen to depend on the relative convexity of schedule delay cost. The condition for the bracketed term to be positive is $2 > -Xg''/g'$, where the right-hand side is the elasticity of the marginal schedule delay cost with respect to output. It holds, therefore, if the g function is linear or concave in the entire region of interest. It will also hold if g is not too convex. We take the view that schedule delay cost is not likely to be highly convex. To see this, let $g(X) = aX^{-\epsilon}$, with $\epsilon > 0$. Then the bracketed term in (8) is positive if $\epsilon < 1$. It can be easily seen that, provided frequency is directly related to traffic volume, ϵ is the same as the elasticity of schedule delay cost with respect to flight frequency. Since the latter is estimated as 0.46 by Douglas and Miller (1974) and others, the bracketed term is positive.

We shall analyse the overall profit effect of switching from a linear to a hub-spoke network for each firm. Unfortunately, it is extremely hard to compare profits of linear and hub-spoke networks directly, even in some special cases. To overcome this difficulty, we introduce differential techniques. Notice that both C^i and π^i are well defined when $\theta^i = 0$ or 1. Furthermore, since C^i is linear in θ^i, for any value of θ^i between 0 and 1, C^i should also represent a conceivable cost function, and therefore, π^i should represent a conceivable profit function. Given these observations, switching from a linear to a hub-spoke network can be calculated as the integral of small changes $d\theta^i$. Such a small change may be referred to as 'infinitesimal hubbing.' It turns out to be easy to sign the profit effect of an infinitesimal hubbing. Consequently, the overall profit effect of the network switch can be determined as well because it will have the same sign as the profit effect of an infinitesimal hubbing whenever the latter sign does not change in the range $0 \leqq \theta^i \leqq 1$, a condition that one can check. For much of the analysis, therefore, we shall treat θ^i as a continuous variable between 0 and 1.

III. MONOPOLY

Although we are concerned principally with the rivalry between firms, the monopoly case serves as a useful base for comparison. It can easily be shown that the network decision by a monopolist (who is unconcerned with entry) is based solely on a total cost comparison between linear and hub-spoke systems. The monopolist will form a hub-spoke network if switching from a linear to a hub-spoke network reduces its total cost. It is useful to take a closer look at this cost differential, which can be written as, using (12) and (13),

$$C^L - C^H = \left[\sum_{k=1}^{3} c_k(x_k) - \left(\sum_{k=1}^{2} c_k(X_k) + c_h\right)\right] + \left[\sum_{k=1}^{3} g_k(x_k)x_k - \left(\sum_{k=1}^{2} g_k(X_k)X_k + \gamma x_3\right)\right]. \tag{15}$$

The first bracket on the right-hand side of the equation represents the differential in production costs between a linear and a hub-spoke network, whereas the second bracket represents the differential in passenger inconvenience costs. Clearly, the more significant the economies of traffic density are, the more likely it is that the hubbing strategy will be adopted. Now suppose that the production costs are the same under the two networks, so that the first bracket in (15) vanishes. Then the network decision will hinge on which network provides travellers with better service. Since hubbing increases the number of flights on the spokes and thus improves quality of service for local passengers, a sufficient condition for the monopolist to choose to hub is that its connecting passengers receive at least the same quality of service as non-stop flights provide. This would be the case, for example, if the IJ market is rather 'thin' relative to markets IH and JH. Hubbing would improve service for the IJ passengers, in this case, by significantly reducing their schedule delay costs. On the other hand, if IJ is a large market, or if the connecting causes substantial inconvenience (a great deal of extra travel time), then we would expect the carrier to offer non-stop service between I and J and consequently form a linear network.

IV. THE STRATEGIC ADVANTAGE OF HUBBING

We now explore the strategic issues involved in the choice of networks by examining the subgame perfect equilibrium of the two-stage networking game specified in section II.[13]

To solve for this duopoly equilibrium, we start with the second-stage competition. In this stage, firms simultaneously choose their output vectors to maximize profits, taking the route structure of each firm (θ^A, θ^B) as given. The Cournot equilibrium is characterized by first-order conditions (subscripts denoting vector partial derivatives),

$$\pi_i^i(x^A, x^B; \theta^i) = 0, \tag{16}$$

and second-order conditions, that is, the 3×3 Hessian matrices $\pi_{ii}^i \equiv (\partial^2\pi^i/\partial x_k^i \partial_l^i)$ are negative definite, $i = A, B$. As is discussed in the appendix, regularity conditions are imposed so that the equilibrium exists and is stable.

The comparative static effects of the network variable θ^i on the equilibrium outputs, denoted $x^A(\theta^A, \theta^B)$ and $x^B(\theta^A, \theta^B)$, are derived in proposition 1 (the proof is given in the appendix). These comparative static effects are central to the subsequent analysis of the paper.

PROPOSITION 1. *Assume that switching from a linear network to a hub-spoke network does not increase firm i's marginal cost in the connecting market. Then,*

$$\frac{\partial x^i(\theta^A, \theta^B)}{\partial \theta^i} > 0, \quad \frac{\partial x^j(\theta^A, \theta^B)}{\partial \theta^i} < 0. \tag{17}$$

Thus, switching from a linear to a hub-spoke network will increase firm i's own output, while simultaneously decreasing its rival's output, in each market.

Proposition 1 gives a strong result: switching from a linear to a hub-spoke network will increase the carrier's own outputs, while simultaneously decreasing its rival's outputs, in *all* three markets. The sufficient condition for this result, that the network switch does not increase the carrier's marginal cost in the connecting market, will hold if the traffic density effect of hubbing is sufficiently strong. In

13 We note that the 'multiproduct' (vector) method used in this section may be useful in examining other settings of multiproduct oligopoly rivalry.

fact, a look at the proof indicates that this condition is not necessary for the result and small deviations from it will not undermine the result.

The intuition associated with this result is as follows. With the network effect, an infinitesimal hubbing raises marginal profitability of local outputs by lowering marginal cost of production and/or improving quality of service (hence, raising marginal revenue). This, together with the condition that the network switch does not lower marginal profitability of connecting output, allows the carrier to commit to greater outputs in all three markets. Since the firm's outputs are strategic substitutes in each market, such a commitment would induce a contraction in the rival's outputs. In effect, hubbing is a top-dog strategy in the sense of Fudenberg and Tirole (1984), which allows the hubbing carrier to be tough (more aggressive) in the product market competition.

Network structures, therefore, influence the subsequent market share rivalry among firms, which in turn can affect their overall profitability. The strategic interaction among firms in selecting their network type takes place in the first stage. Taking the second-stage equilibrium outputs into account, firm i's profit, denoted ϕ^i, can be written as

$$\phi^i(\theta^A, \theta^B) = \pi^i(x^A(\theta^A, \theta^B), x^B(\theta^A, \theta^B); \theta^i). \tag{18}$$

The network equilibrium arises when each firm chooses its profit-maximizing network, taking the network of the other as given at the equilibrium value. The following result gives a sufficient condition for choosing a hub-spoke network in a duopoly.

PROPOSITION 2. *Assume that switching from a linear network to a hub-spoke network does not increase the firm's total cost and its marginal cost in the connecting market. Then the firm will use a hub-spoke network rather than a linear network.*

Proof. We prove the result by showing that $\partial\phi^i/\partial\theta^i > 0$. From (18),

$$\begin{aligned}\frac{\partial\phi^i}{\partial\theta^i} &= \sum_{k=1}^{3}\frac{\partial\pi^i}{\partial x_k^i}\frac{\partial x_k^i}{\partial\theta^i} + \sum_{k=1}^{3}\frac{\partial\pi^i}{\partial x_k^j}\frac{\partial x_k^j}{\partial\theta^i} + \frac{\partial\pi^i}{\partial\theta^i} \\ &= \left[\sum_{k=1}^{3}\frac{\partial\pi^i}{\partial x_k^j}\frac{\partial x_k^j}{\partial\theta^i}\right] + [C^{iL} - C^{iH}],\end{aligned} \tag{19}$$

where the second equality follows from (16) and (14). If switching from a linear to a hub-spoke network does not increase i's total cost, then the second bracketed term in (19) is non-negative. Further, since $\partial\pi^i/\partial x_k^j = x_k^i(\partial d_k^i/\partial x_k^j)$ is negative by (3), the summation in (19) involving x^j is strictly positive by proposition 1. This establishes that $\partial\phi^i/\partial\theta^i > 0$. QED

Proposition 2 shows that hubbing can be used as both an offensive and a defensive strategy in airline network rivalry. It improves a firm's profit, compared with linear routing, when the rival chooses a linear network; it defends the firm when the rival engages in hubbing. In effect, under the specified conditions, hubbing is the firm's dominant strategy.

Furthermore, a look at the proof reveals that the effect of a change in θ^i on own profit ϕ^i can be split into two parts: (i) the direct effect of the shift in the profit function itself, $\partial\pi^i/\partial\theta^i$, and (ii) the indirect effect of the shift in the marginal profits, which in turn changes the duopoly equilibrium. The first part is the 'total cost effect' of hubbing, which is represented by the second (bracketed) term on the right-hand side of (19). This effect has already been identified in section III: a monopoly firm will form a hub-spoke network if switching from a linear to a hub-spoke network reduces its total cost. (Recall that cost includes both production and passenger inconvenience costs.) However, the other effect, referred to as the 'strategic effect' of hubbing, is unique to an oligopoly. The strategic effect is represented by the first term in (19), which is positive so long as the network switch does not increase a firm's marginal cost in the connecting market. In that case, hubbing by firm A (say), given firm B's network choice, makes it supply more outputs in both local and connecting markets. The output expansion by A is credible, so B's best response is to supply less outputs. Since the two firms offer substitutable products in any given market, a fall in B's outputs will raise A's profit.

More interesting perhaps is the question of whether the indirect strategic effect augments or counteracts the direct cost effect, that is, whether parametric shifts $d\theta^i$ will shift the total and the marginal costs in the same direction. As indicated earlier, if the traffic density effect of hubbing is sufficiently strong, then switching from a linear to a hub-spoke network normally reduces both the total and the marginal costs. Thus, if the network switch lowers total cost, the strategic interaction usually augments hubbing. It is worth pointing out, however, that a positive cost effect is not a necessary condition for an airline to choose to hub. In effect, an infinitesimal hubbing by i, given the rival's network choice, will improve its profit if the second term on the right-hand side of (19) is zero but the first term is positive. This does hold for some specifications of production cost and schedule delay cost.[14] Moreover, it is possible to construct numerical examples that show that even if switching from a linear to a hub-spoke network *increases* total cost, hubbing remains the firm's dominant strategy. Essentially, the network switch, though it raises total cost, may nevertheless reduce the operator's marginal cost in the connecting market. In these cases firms do not minimize total costs (production and passenger inconvenience costs) in their choice of route structure, and the use of hub-spoke networks is purely for strategic purposes.[15]

14 More specifically, if production cost can be written as $c_k^i(x_k^i) = \mu_k^i + \nu_k^i x_k^i$ with $\mu_3^i = c_h^i$ and $\nu_3^i = \nu_1^i + \nu_2^i$, and if schedule delay cost can be written as $g_k^i(x_k^i) = \alpha^i - \beta^i x_k^i$, with $\alpha^i + \gamma^i = \beta^i \lambda^i$ and λ^i being determined by the equation $2x_1^i + 2x_2^i + x_3^i = \lambda^i$, where x_k^i are the (second-stage) equilibrium outputs for any given θ^i, then $C^{iH}(x^i) = C^{iL}(x^i)$ and $\partial C^{iH}(x^i)/\partial x_3^i \leqq \partial C^{iL}(x^i)/\partial x_3^i$ at θ^i.

15 Such hubbing may be called 'strategic hubbing.' A natural question then concerns whether such strategic use of hub-spoke networks is against the public interest. Since strategic hubbing does

TABLE 1
Profit matrix in the networking game: an example

firm 1 \ firm 2	L	H
L	2.15, 2.15	1.86, 2.22
H	2.22, 1.86	1.90, 1.90

Although proposition 2 has established that, under the specified conditions, hubbing will be the dominant strategy for a firm, it is not always true that $\phi^i(1,1) > \phi^i(0,0)$. That is, it is not guaranteed that firms are better off if they both choose a hub-spoke network than if they both choose a linear network. Because of the network externality, hubbing tends to increase output beyond the level produced under a linear network, thereby lowering prices. When both firms engage in hubbing, the strategic gains tend to offset each other and both will be worse off if the cost gain from hubbing is small. Formally, we have (the proof is in the appendix):

PROPOSITION 3. *Rivalry in networking can result in a Prisoners' Dilemma for airlines.*

A numerical example is used below to illustrate this result. Assume that demand is linear as follows:

$$d_k(x_k^A, x_k^B) = a - (x_k^A + x_k^B), \qquad k = 1, 2, 3. \tag{20}$$

Assume further that production cost $c_k^i(\cdot)$ is linear and that schedule delay cost is also linear:

$$g_k^i(x_k^i) = \alpha - \beta x_k^i, \qquad k = 1, 2, 3. \tag{21}$$

An additional useful simplification is to set $c_k^i(\cdot)$ equal to zero. Given these specifications, the explicit expressions of equilibrium profits can be obtained for each firm under each of the four network configurations (H,H), (L,L), (H,L) and (L,H). In particular, when $a = 3$, $\alpha = 0.5$, $\beta = 0.1$, $\gamma = 0.05$ and $c_h^A = c_h^B = 0.05$, the equilibrium pay-off matrix for each firm is reported in table 1. The table shows that although hub-spoke routing is a dominant strategy for both firms, both are worse off using a hub-spoke network than using a linear network. The situation is a classic Prisoners' Dilemma.[16]

not minimize total costs, it tends to reduce welfare. On the other hand, there is also a tendency, owing to the externality effect of hubbing, for the strategic behaviour to increase outputs, which is socially desirable given that prices exceed marginal costs in an oligopoly. The net impact on social welfare depends on the relative strength of these two partially offsetting effects. We see analysis of the welfare effects of hubbing as an interesting and important extension of the analysis presented here, although it is beyond the scope of the present paper.

16 For comparison, a monopolist in the same situation will be better off by using a hub-spoke network, with a profit equal to 5.44, than by using a linear network, with a profit equal to 5.21.

V. HUBBING AS ENTRY DETERRENCE

In the preceding section we have shown that hubbing helps a firm gain strategic advantages in market share rivalry. The following result indicates that hubbing can also be used by one firm to harm another.

PROPOSITION 4. *Assume that switching from a linear network to a hub-spoke network does not increase the firm's marginal cost in the connecting market. Then switching from a linear to a hub-spoke network will reduce its rival's profit.*

Proof. From (18) (interchange i and j) and (16),

$$\frac{\partial \phi^j}{\partial \theta^i} = \sum_{k=1}^{3} \frac{\partial \pi^j}{\partial x_k^i} \frac{\partial x_k^i}{\partial \theta^i}. \tag{22}$$

Since $\partial \pi^j / \partial x_k^i$ is negative by (3), it follows, using proposition 1, that $\partial \phi^j / \partial \theta^i < 0$. QED

This result has important implications for entry deterrence. Suppose that a firm (say firm A) has an exogenously given opportunity to choose its network structure prior to the entry and network decision of a potential entrant (firm B) and that there exists a sunk cost associated with an entry into a city-pair market, denoted K. The sunk entry cost can include route-specific irrecoverable advertising and promotional expenditures, investments in initial operations (e.g., the aircraft time necessary to operate for a trial period), and short-run losses associated with inauguration of service on a new route (see Bailey et al. 1985; Levine 1987; Butler and Huston 1989). Then proposition 4 suggests that for certain ranges of entry cost, a possible entry by the rival will be pre-empted if and only if the incumbent chooses hub-spoke routing. In other words, an incumbent firm can use hub-spoke networks as a device to deter potential entry and will do so if the incumbent is better off with hubbing and no entry than with no hubbing and entry.

In fact, we can show further that the threat of entry along can give rise to a hub-spoke network as opposed to a linear network. This result is obtained if (i) in the absence of a threat of entry hubbing by the incumbent is not profitable, (ii) linear networking exists and entry is profitable, (iii) hubbing exists and entry is not profitable, and (iv) the incumbent earns a greater profit in the case where hubbing and no entry exist than in the case where linear networking and entry exist. To illustrate that these conditions can be satisfied simultaneously, we present an example in which entry into a single spoke (e.g., HI) marked by firm B is possible. In the example, production cost $c_k^i(\cdot)$ is assumed to be linear and, without loss of generality, is further set equal to zero, whereas demand and schedule delay costs are given by (20) and (21), respectively. When $a = 3$, $\alpha = 0.5$, $\beta = 0.1$, $\gamma = 0.3$, $c_h^A = 0.05$, and $K = 0.6$, all the above four conditions are satisfied.[17]

17 In this example we have implicitly assumed that the entrant can enter only into a single-spoke

In the above example the incumbent would prefer a linear network to a hub-spoke network if there were no threat of entry. With potential entry, the incumbent prefers hubbing to linear networking, since it earns a higher profit with hubbing and no entry than with linear networking and entry. We have thus shown that the threat of entry by rival firms can serve as an additional independent reason for the choice of hub-spoke networks.

This result (i.e., that even if hubbing raises total cost, it might be pursued to deter entry) has strong ties to the original insight of Dixit (1980) on the role of capital investment in entry deterrence. Essentially, an incumbent firm that chooses to hub is trading off higher fixed costs for lower marginal costs (and/or a better product via demand-side network externalities, as in the above example). These lower marginal costs credibly commits it to producing at a higher rate and thereby reduces the profitability of entry.

The foregoing analysis suggests that in today's highly competitive airline markets, a linear route system is vulnerable to attack from rival firms, whereas a hub-spoke network is more 'defensible' against entry. Dominant carriers at their hubs can channel traffic from a large number of cities onto a particular spoke segment. An entrant to the segment would be unable to access this traffic and, as a result, would be confined to a small market share. The small market share could result in a failure for the entrant if its post-entry profit is less than the sunk entry cost; in these cases such entry would be unprofitable ex ante. To launch a viable operation in an incumbent's hub, a major assault by an entrant, in which all spokes are contested at once and a hub-spoke network of its own is formed, generally is required.[18] A major assault also is needed if the hub markets as a whole are likely to support only one airline (in the sense that the markets are profitable for one firm if it is the only entrant, but they will be unprofitable if both firms enter and must share the hub). In that case a would-be entrant at the hub must be prepared to displace the incumbent. Since doing so requires an enormous investment from the entrant and is highly risky (Butler and Huston 1989), new entrants, in practice, do not appear to compete in the hubbing airline's 'home' markets, that is, spoke segments from its hub to other non-hub cities it serves. Instead, new entries that do occur seem to be limited to service to and from other airlines' hubs. As a result, airlines usually compete for the traffic between hub cities 'head to head' and the traffic between non-hub cities through interhub competition. It is on routes with the hub at one endpoint that the airline will have the least competition and the most market power (e.g., Borenstein 1989; Berry 1990; Evans and Kessides 1993a). Our analysis offers an explanation of the phenomenon.

market. If the entrant can choose to enter any of the three markets, then entering into a one-spoke market may not be the most profitable alternative. In this case we need to calculate profits for the other entry possibilities. We note that our basic result extends to this case.

18 Using the present framework we can construct numerical examples that show that for given fixed production costs on each route and given demand levels in each city-pair market, a major assault by an entrant is generally more profitable than entry into only one of the markets. Thus, given fixed entry costs for each market, a major assault would be more likely to succeed than an invasion of a single spoke.

VI. CONCLUDING REMARKS

Our main objectives in this paper are to contribute to the understanding of the dramatic growth of hub-spoke networks under deregulation, and to develop a methodology that can be used in analysing multiproduct oligopoly for network-oriented firms. In our simple three-city model, we found that for a monopolist who is unconcerned with entry, the network choice is based solely on production cost and service quality considerations. In an oligopolistic setting or if the monopolist faces the threat of potential entry, the cost and quality considerations remain but strategic effects must also be taken into account. The significant point is that the firm that chooses a hub-spoke network may benefit strategically by altering the future terms of interfirm rivalry by modifying its own, and its opponent's, output decisions. We found that if switching from a linear to a hub-spoke network reduces total cost (which includes both the airline costs and the costs to passengers resulting from inconvenience of travel), the pursuit of strategic advantages by an airline usually augments the need for hubbing. It is possible that even if hubbing raises total cost, it is still pursued by the airline, either because hubbing is a dominant strategy in an oligopoly or because the choice of hubbing will be useful in deterring entry.

Owing to the strategic advantages to be gained by increasing the degree of hubbing, the dominant carrier at an airport may have an incentive for 'overhubbing' – hubbing over and above the extent that can be justified by cost and/or service quality advantages. This translates into a potential for the dominant carrier to overbid the price of airport (runway and gate) slots beyond their marginal values, which has important implications for antitrust administrations concerning the allocation of airport slots through competitive auctions. This argument may lead to a justification for reserving certain blocks of airport slots for new entrants.

The paper suggests some interesting directions for future research. First, it may be possible to measure, econometrically, the degree of overhubbing and the effect of overhubbing on social welfare. A possible starting point for such research would be to measure the revealed marginal value of non-stop flights and connecting flights (via a hub) between major cities: for example, the direct Los Angeles – New York flights versus the connecting flights via Chicago, Denver, or Dallas. The second area of future research would be to extend our results on the strategic advantage of hubbing to the case where carriers compete using different locations for their hubs with some overlapping geographic regions to serve. We believe that the basic framework and insight of this paper would be applicable to such a case, although the analysis becomes much more complex than the case treated in this paper.

APPENDIX

We now consider the regularity conditions under which the Cournot equilibrium exists and is stable. Equation (16) implicitly defines firm i's reaction function, denoted $x^i = R^i(x^j; \theta^i)$. Letting $x \equiv [x^A, x^B]$ and $T(x; \theta^A, \theta^B) \equiv [R^A(x^B; \theta^A), R^B(x^A; \theta^B)]$, then the Cournot equilibrium will satisfy: $x = T(x; \theta^A, \theta^B)$. Apparently, given

(θ^A, θ^B), T is a mapping from real six-dimensional linear space to itself. Furthermore, the derivative of T is a matrix given by

$$T' = \begin{bmatrix} 0 & R_B^A \\ R_A^B & 0 \end{bmatrix},$$

where R_B^A (R_A^B) represent the derivative matrices of firm A's (B's) reaction functions. We assume that the Cournot equilibrium exists (see Zhang and Zhang 1994, proposition 1, for the existence conditions). We further assume that in the entire region of interest, T is continuously differentiable and

$$\max_i |\lambda_i| < 1, \tag{A1}$$

where $|\lambda_i|$ is the modulus of the ith eigenvalue of T'. Condition (A1) implies that T is a contraction mapping. It is imposed to ensure that the multiproduct Cournot equilibrium is stable under the standard adjustment process (Zhang and Zhang 1994).

Proof of proposition 1

Without loss of generality we can set $i = A$. Differentiating (16) (with $x^i = x^i(\theta^A, \theta^B)$) with respect to θ^A we have by matrix notation:

$$\frac{\partial x^A}{\partial \theta^A} = -\left(I - (\pi_{AA}^A)^{-1}\pi_{AB}^A(\pi_{BB}^B)^{-1}\pi_{BA}^B\right)^{-1}(\pi_{AA}^A)^{-1}\pi_{A\theta}^A, \tag{A2}$$

$$\frac{\partial x^B}{\partial \theta^A} = \left(I - (\pi_{BB}^B)^{-1}\pi_{BA}^B(\pi_{AA}^A)^{-1}\pi_{AB}^A\right)^{-1}(\pi_{BB}^B)^{-1}\pi_{BA}^B(\pi_{AA}^A)^{-1}\pi_{A\theta}^A, \tag{A3}$$

with $\pi_{A\theta}^A \equiv (\partial^2\pi^A/\partial x_k^A \partial\theta^A)$. First we note that the matrix π_{BA}^B has non-zero elements only in the diagonal, and the kth element in the diagonal, $(\pi_{BA}^B)_{kk} = \partial^2\pi^B/\partial x_k^B \partial x_k^A$, is negative by (10). Likewise, π_{AB}^A is a negative diagonal matrix.

Next, the inverse of the Hessian matrix, $(\pi_{AA}^A)^{-1}$ can be expressed as

$$(\pi_{AA}^A)^{-1} = \frac{1}{\Delta^A}\begin{bmatrix} \pi_{22}^A\pi_{33}^A - (\pi_{23}^A)^2 & \pi_{13}^A\pi_{23}^A & -\pi_{13}^A\pi_{22}^A \\ \pi_{13}^A\pi_{23}^A & \pi_{11}^A\pi_{33}^A - (\pi_{13}^A)^2 & -\pi_{11}^A\pi_{23}^A \\ -\pi_{13}^A\pi_{22}^A & -\pi_{11}^A\pi_{23}^A & \pi_{11}^A\pi_{22}^A \end{bmatrix},$$

where Δ^A is the determinant of π_{AA}^A. Applying the second-order condition and condition (9), we obtain that all the diagonal elements of $(\pi_{AA}^A)^{-1}$ are negative while the off-diagonal ones are non-positive. (π_{13}^A, for instance, can be written as $\theta^A\pi_{13}^{AH} + (1-\theta^A)\pi_{13}^{AL}$. Since π_{13}^{AL} is zero, (9) implies that $\pi_{13}^A \geqq 0$.) Similarly, $(\pi_{BB}^B)^{-1}$ also is a non-positive matrix.

Differentiating firm A's first-order condition with respect to x^B yields $R_B^A = -(\pi_{AA}^A)^{-1}\pi_{AB}^A$. Since both $(\pi_{AA}^A)^{-1}$ and π_{AB}^A are non-positive, R_B^A is non-positive (with diagonal elements being strictly negative). Similarly, $R_A^B = -(\pi_{BB}^B)^{-1}\pi_{BA}^B$ is non-positive. Using R_B^A and R_A^B, (A2) and (A3) can be rewritten as

$$\frac{\partial x^A}{\partial \theta^A} = -(I - R)^{-1}(\pi_{AA}^A)^{-1}\pi_{A\theta}^A \tag{A4}$$

$$\frac{\partial x^B}{\partial \theta^A} = -(I - \tilde{R})^{-1}R_A^B(\pi_{AA}^A)^{-1}\pi_{A\theta}^A, \tag{A5}$$

where both $R \equiv R_B^A R_A^B$ and $\tilde{R} \equiv R_A^B R_B^A$ are non-negative matrices. Further, since

$$T'T' = \begin{bmatrix} R & 0 \\ 0 & \tilde{R} \end{bmatrix},$$

condition (A1) implies that the magnitude of the eigenvalues of matrix R must be less than unity. Hence, by Neumann lemma (see, e.g., Ortega and Rheinboldt 1970), $(I - R)^{-1}$ exists and

$$(I - R)^{-1} = I + R + R^2 + \cdots + R^n + \cdots.$$

Since R is non-negative, the series $\sum R^n$ must also converge to a non-negative matrix. Therefore, $(I - R)^{-1}$ is non-negative. By similar reasoning, $(I - \tilde{R})^{-1}$ is also non-negative.

Thus, $\partial x^A/\partial\theta^A$ ($\partial x^B/\partial\theta^A$, respectively) is the product of the vector $\pi_{A\theta}^A$ and a non-negative (non-positive, respectively) matrix, with diagonal elements being strictly positive. We now show that both of the first two elements of the vector $\pi_{A\theta}^A$ are positive, that is,

$$\frac{\partial^2 \pi^A}{\partial x_k^A \partial \theta^A} > 0, \qquad k = 1, 2. \tag{A6}$$

The above inequalities can be established using the complementarity condition (9). Integrating both sides of the following inequality (which holds because of (9) and $\partial^2\pi^{AL}/\partial x_k^A \partial_3^A = 0$)

$$\frac{\partial^2 \pi^{AH}}{\partial x_k^A \partial x_3^A} > \frac{\partial^2 \pi^{AL}}{\partial x_k^A \partial x_3^A}$$

with respect to x_3^A, and noting that for given x^B, $\partial\pi^{AH}/\partial x_k^A = \partial\pi^{AL}/\partial x_k^A$ at $x^A = (x_1^A, x_2^A, 0)$, we obtain

$$\frac{\partial \pi^{AH}}{\partial x_k^A} - \frac{\partial \pi^{AL}}{\partial x_k^A} = \int_0^{x_3^A} \frac{\partial^2 \pi^{AH}}{\partial x_k^A \partial x_3^A}\, dx_3^A - \int_0^{x_3^A} \frac{\partial^2 \pi^{AL}}{\partial x_k^A \partial x_3^A}\, dx_3^A > 0. \tag{A7}$$

Then, by definition $\pi^A = \theta^A \pi^{AH} + (1-\theta^A)\pi^{AL}$ and by (A7) we obtain (A6). Finally, the last element of $\pi^A_{A\theta}$ can be derived as

$$\frac{\partial^2 \pi^A}{\partial x_3^A \partial \theta^A} = \frac{\partial C^{AL}}{\partial x_3^A} - \frac{\partial C^{AH}}{\partial x_3^A}. \tag{A8}$$

This element is non-negative if switching from a linear to a hub-spoke network does not increase A's marginal cost in the connecting market.

In conclusion, it is clear that a sufficient condition for (A4)'s being non-negative and (A5)'s being non-positive is that expression (A8) is non-negative. Proposition 1 then follows immediately if we note that all the diagonal elements in matrices under consideration are either strictly positive or strictly negative. QED

Proof of proposition 3
Consider the auxiliary function (set $i = A$),

$$\phi^A(\theta^A, \theta^A) = \pi^A(x^A(\theta^A, \theta^A), x^B(\theta^A, \theta^A); \theta^A).$$

Totally differentiating ϕ^A with respect to θ^A and applying (16) yields

$$\frac{d\phi^A}{d\theta^A} = \sum_{k=1}^{3} \frac{\partial \pi^A}{\partial x_k^B} \frac{dx_k^B}{d\theta^A} + \frac{\partial \pi^A}{\partial \theta^A}. \tag{A9}$$

Under the conditions of proposition 2, we have $\partial\pi^A/\partial\theta^A = C^{AL} - C^{AH} \geqq 0$. Differentiating the first-order conditions with respect to θ^A after replacing θ^B with θ^A, solving for $dx^B/d\theta^A$ and substituting, we get

$$\sum_{k=1}^{3} \frac{\partial \pi^A}{\partial x_k^B} \frac{dx_k^B}{d\theta^A} = \frac{\partial \pi^A}{\partial x^B}(I - \tilde{R})^{-1}(\pi^B_{BB})^{-1}(\pi^B_{BA}(\pi^A_{AA})^{-1}\pi^A_{A\theta} - \pi^B_{B\theta}). \tag{A10}$$

Under the conditions of proposition 2, the matrix product $(\partial\pi^A/\partial x^B)(I-\tilde{R})^{-1}(\pi^B_{BB})^{-1}$ gives a non-negative matrix. However, $\pi^B_{BA}(\pi^A_{AA})^{-1}\pi^A_{A\theta} - \pi^B_{B\theta}$, being the difference of two non-negative matrices, in general will have an ambiguous sign. Hence, the sign of $d\phi^A(\theta^A, \theta^A)/d\theta^A$ is ambiguous, and in the cases where $\phi^A(1, 1) < \phi^A(0, 0)$, a Prisoners' Dilemma will arise. QED

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