COST RECOVERY IN A HUB-AND-SPOKE AIRPORT NETWORK

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1. INTRODUCTION

The airline deregulation in the United States and other countries gave the freedom for airline management to set up efficient hub-and-spoke airport networks. The hub-and-spoke network is likely to intensify domestically and internationally as airlines attempt to improve efficiency of their operations and quality of services to customers. In the near future, we will see global air carrier alliances with hub-and-spoke system extending beyond national boundaries in order to serve intercontinental passengers more efficiently and conveniently.

This will continue to increase congestion at hub airports while some spoke airports will continue to be underutilized. Optimal pricing rule (e.g., social marginal cost pricing or peak period pricing) is likely to lead financial surplus at the hub airport and deficit at spoke airports. Given that the demands for hub and spoke airports are complementary, the optimal pricing of a hub-and-spoke airport network as a system may require subsidization of the money-losing spoke airports from the hub airport. This is in fact consistent with the current practice of airport financing in many countries including Canada.

When an airport is treated as a single operating unit, the socially optimal pricing scheme has been discussed extensively in the literature. Carlin and Park (1970), Glaister (1974), Keeler and Small (1977), Borins (1984), Gillen, Oum and Tretheway (1987), and Park (1989) are just a few examples. Mohring and Harwitz (1962), studying highway cost recovery, first established that if capacity is divisible, marginal cost pricing of the infrastructure will lead to financial breakeven. Morrison (1983) arrived at the same conclusion for an airport characterized by multiple user and multiple period, in which congestion occurs during peak periods. On the other hand, Oum and Zhang (1990) find that when capacity is not perfectly divisible, social marginal cost pricing does not necessarily lead to the exact cost recovery for the airports.

If airport capacity is fixed, at least in the short run, then social marginal cost pricing will likely create surplus for hub airports where congestion costs are substantial. If financial breakeven condition is imposed on the airport, constrained optimization will lead to Ramsey pricing scheme (See Oum and Tretheway (1988), for example). This paper extends the literature by considering the optimal pricing scheme over a system of hub-and-spoke airports for which traffic demands are interrelated.

If airports are characterized by lumpy, indivisible capacity, fixed in the short run, then cost recovery is not guaranteed by social marginal cost pricing. However, imposing financial breakeven condition to individual airports may not be a desirable solution. Given the fact that major airlines have formed their route structure based on their hub-and-spoke network, the traffic demands for the hub and spoke airports are complementary. Therefore, social marginal cost pricing in any hub airport without taking into account the spoke airports will have an external effect on the traffic demands at the apoke airports. This externality can only be eliminated by pricing the hub-and-spoke airports jointly as a system.

Since hub airports are likely to be congested while spoke airports are underutilized, pricing the system jointly by social marginal cost will make surplus at hub airports and deficit at spoke airports, necessitating a cross-subsidy among the airports. Also, when the system of airports are jointly considered to determine the optimal pricing scheme, it is of practical importance to estimate the consequence on the amount of total charges a typical airline (with a hub-and-spoke network) will have to pay as compared to the amount it would pay under the independent pricing regime.

In section 2, we will model the characteristics of the first best airport pricing in a hub-and-spoke system without financial constraint on the system, and investigate how the conventional pricing theory must be modified in order to deal with the intensifying hub-and-spoke network. In section 3, an overall financial constraint will be imposed to the model and second best solutions are examined. The impact on the airlines of the jointly optimal pricing for the hub-and-spoke system under the financial breakeven condition is discussed in section 4. Finally, section 5 concludes the paper.

2. MODEL WITH NO FINANCIAL CONSTRAINT

Consider an airport network consisting of one hub airport and n spoke airports. Let demand for the jth spoke airport be

$$D_j = D_j(p_j+2p_h), \qquad j=1,2,...,n$$

where p_j is the airport charge at the jth spoke and p_h is the airport charge at the hub. For simplicity, we assume that all the traffic originating from the spoke airports transfers at the hub. Therefore, if demand is expressed in number of passenger movements (one landing or takeoff is counted as one movement), any passenger leaving from one spoke airport will have one movement of taking-off at the spoke plus two movements at the hub (one landing and one subsequent taking-off). Final destination is assumed to be outside the hub-spoke system under consideration (possibly, another hub or its spoke airport). The airport user charge is expressed on a per movement basis. The demand for the hub airport is

$$D_h = G(p_h) + 2\sum_{j=1}^{n} D_j$$

where G(.) is the traffic originating from the hub, and the sum of D_j is the transit traffic originating from the spoke airports. Airport operating costs and capacity costs for each airport are, respectively,

$$c_h D_h,\ r_h K_h, \quad and \quad c_j D_j,\ r_j K_j, \quad j=1,2,...,n$$

where K_j is the capacity of the airport j. For mathematical simplicity, in the following analysis, we will consider only the symmetric case. Specifically, we will assume

$$D_j(\cdot) = D_s(\cdot), \quad K_j = K_s, \quad c_j = c_h = c, \quad r_j = r_h = r, \quad j=1,2,...,n.$$

Consider two pricing regimes. In regime I, each hub or spoke airport is priced separately while in regime II, hub and spoke airports are priced as a system.

2.1. Regime I

When hub and spoke airports are priced separately, the objective of the hub airport authority should be maximizing the following net social benefits:

$$\max_{p_h} \int_{p_h} G(p)dp + n\int_{2p_h} D_s(p_s+p)dp$$

$$+ p_h G + 2p_h n D_s - cD_h - rK_h - f\left(\frac{D_h}{K_h}\right)$$

where

$$D_h = G(p_h) + 2nD_s(p_s+2p_h)$$

and f is the external congestion costs, a function of volume/capacity ratio.

The first order condition for this problem can be derived as follows:

$$4p_h n D_s' + p_h G' - \left(c+\frac{f_h'}{K_h}\right)[4nD_s' + G'] = 0,$$

or

$$p_h = c + \frac{f_h'}{K_h}$$

where f_h denotes $f(D_h/K_h)$. This is the social marginal cost pricing.

For any spoke airport, the optimization problem can be expressed as:

$$\max_{p_s} \int_{p_s} D_s(2p_h+p)dp + p_s D_s$$

$$- cD_s - rK_s - f\left(\frac{D_s}{K_s}\right)$$

The first order condition can be written as:

$$p_s = c + \frac{f_s'}{K_s}$$

where f_s denotes $f(D_s/K_s)$. Generally, the hub airport has a much higher volume of traffic than each of the spoke airports, hence, congestion is likely to build up in the hub while spoke airports have relatively little congestion. In this case, we have

$$\frac{f_h'}{K_h}D_h > rK_h, \quad and \quad \frac{f_s'}{K_s}D_s < rK_s$$

Without loss of generality, we may also assume that $f' > 0$, $f'' > 0$.

Obviously, the hub airport will enjoy financial surplus while the spoke airports will suffer from financial loss. To keep breakeven in the operation, the spoke airports will have to charge average costs, i.e.

$$p_s = c + \frac{rK_s}{D_s}.$$

2.2. Regime II

When hub and spoke airports are considered as a system, the objective of the airports authorities should be:

$$\max_{p_h, p_s} \int_{p_h} G(p)dp + p_h G + n\left[\int_{p_s+2p_h} D_s(p)dp + (p_s+2p_h)D_s\right]$$

$$- cD_h - rK_h - f\left(\frac{D_h}{K_h}\right) - n\left[cD_s + rK_s + f\left(\frac{D_s}{K_s}\right)\right]$$

where

$$D_h = 2nD_s + G$$

The first order conditions are:

$$\left(p_h - c - \frac{f_h'}{K_h}\right)(4nD_s' + G') + 2n\left(p_s - c - \frac{f_s'}{K_s}\right)D_s' = 0 \tag{1}$$

$$D_s'\left[2\left(p_h - c - \frac{f_h'}{K_h}\right) + \left(p_s - c - \frac{f_s'}{K_s}\right)\right] = 0 \tag{2}$$

Substituting (2) into (1) yields:

$$\left(p_h - c - \frac{f_h'}{K_h}\right)G' = 0$$

which leads to

$$p_h = c + \frac{f_h'}{K_h}$$

substituting the above result into (2) gives

$$p_s = c + \frac{f_s'}{K_s}$$

i.e., social marginal cost pricing should be used on both hub and spoke airports.

2.3. Welfare and Financial Consequences of Regime Change without Financial Constraint

Apparently, changing from regime I to regime II is welfare enhancing, because social marginal cost pricing replaces average cost pricing in the spoke airports. However, the financial consequences are more complicated.

As the spoke airports charge social marginal costs, the price of using the spoke airports declines, and demand will increase. On the other hand, increased traffic originating from the spoke airports increases the congestion at the hub, forcing a higher price for using the hub, which will reduce the traffic originating from the hub area. Formally, we have $dp_s < 0$ as the result of a pricing regime change in the spoke airports. In the hub,

$$dp_h = \frac{f_h''}{K_h^2} dD_h$$

$$= \frac{f_h''}{K_h^2}[G' dp_h + nD_s'(2dp_h + dp_s)]$$

$$= \frac{f_h''}{K_h^2}\left[(G' + 2nD_s')dp_h + nD_s' dp_s\right].$$

Solving for dp_h, we get

$$dp_h = \frac{nD_s'(f_h''/K_h^2)dp_s}{1 - (G' + 2nD_s')(f_h''/K_h^2)} > 0.$$

However,

$$2dp_h + dp_s = \left[\frac{2nD_s'(f_h''/K^2)}{1 - (G' + 2nD_s')(f_h''/K^2)} + 1\right] dp_s$$

$$= \frac{1 - G'(f_h''/K^2)}{1 - (G' + 2nD_s')(f_h''/K^2)} dp_s < 0,$$

and it follows that $dD_s > 0$.

Change in total revenue in any spoke airport after regime switching can be written as:

$$dR_s = D_s dp_s + (p_s - c)dD_s$$

$$= D_s\left[\frac{dp_s}{2dp_h + dp_s} - \frac{p_s - c}{2p_h + p_s}\eta\right](2dp_h + dp_s)$$

where η is the elasticity of demand (assumed constant at all of the airports in the system). Previous studies (Gillen, Oum, Tretheway (1987), for example) showed that the elasticities of air traffic with respect to airport charge are quite small (less than 0.1 in absolute value), therefore, the first term in the above bracket is greater than unity while the second term is less than unity. It follows that $dR_s < 0$, i.e. the spoke airport will be in deficit after the regime change.

In the hub, the change in total revenue will be:

$$dR_h = D_h dp_h + (p_h-c)dD_h$$

$$= (G+2nD_s)dp_h + (p_h-c)(dG+2ndD_s)$$

$$= \left[1-\frac{p_h-c}{p_h}\eta\right]Gdp_h + 2nD_s\left[dp_h-\frac{p_h-c}{2p_h+p_s}\eta(2dp_h+dp_s)\right]$$

$$> 0.$$

Taking all the spoke airports and the hub airport jointly as a system, then the change in total revenue due to regime switching is:

$$dR_h+ndR_s$$

$$= G\left[1-\frac{p_h-c}{p_h}\eta\right]dp_h + nD_s\left[1-\frac{2(p_h-c)+(p_s-c)}{2p_h+p_s}\eta\right](2dp_h+dp_s)$$

Since $2dp_h+dp_s$ is negative and dp_h is positive, the sign of the above expression depends on the relative magnitude of the traffic originating from the hub, G, and the sum of traffic originating from all the spoke airports.

3. MODEL WITH FINANCIAL CONSTRAINTS

If the system of hub-spoke airports is constrained to be financially breakeven, then first-best pricing scheme discussed in the previous section may not be feasible. In this section, we investigate the optimal pricing rules under financial constraints. First, consider the case where the hub and spoke airports are subject to separate breakeven conditions.

3.1. Regime I

When the hub and spoke airports are treated separately, each of the airports must satisfy breakeven condition. For the hub, the optimization problem becomes:

$$\max_{p_h} \int_{p_h} G(p)dp + n\int_{2p_h} D_s(p_s+p)dp$$

$$+ p_h G + 2p_h nD_s - cD_h - rK_h - f\left(\frac{D_h}{K_h}\right)$$

$$s.t. \quad (p_h - c)(G + 2nD_s) - rK_h = 0$$

The only feasible solution to this problem is:

$$p_h = c + \frac{rK_h}{D_h}$$

Similarly, the solution to the spoke airports can be written as:

$$p_s = c + \frac{rK_s}{D_s}.$$

3.2. Regime II

When the hub and spoke airports are treated as a system and the financial breakeven condition is imposed onto the system, the optimization problem can be formulated as:

$$\max_{p_h,p_s} \int_{p_h} G(p)dp + p_h G + n\left[\int_{2p_h+p_s} D_s(p)dp + (2p_h+p_s)D_s\right]$$
$$- cD_h - rK_h - f\left(\frac{D_h}{K_h}\right) - n\left[cD_s + rK_s + f\left(\frac{D_s}{K_s}\right)\right]$$

$$s.t.\quad (p_h-c)G + n\left[2(p_h-c)+(p_s-c)\right]D_s - r(K_h+nK_s) = 0$$

The first order conditions for this problem are derived as follows:

$$\begin{cases} (p_h-c-\frac{f_h'}{K_h})(nD_s'+G') + 2n(p_s-c-\frac{f_s'}{K_s})D_s' \\ \quad + \lambda\left\{(p_h-c)(4nD_s'+G') + 2n(p_s-c)D_s' + 2nD_s + G\right\} = 0, \\ D_s'[2(p_h-c-\frac{f_h'}{K_h}) + (p_s-c-\frac{f_s'}{K_s})] \\ \quad + \lambda\left\{[2(p_h-c)+(p_s-c)]D_s' + D_s\right\} = 0, \\ n[2(p_h-c)+(p_s-c)]D_s + (p_h-c)G - r(K_h+nK_s) = 0, \end{cases}$$

which, after some tedius manipulations, lead to the following equations:

$$p_h - c = \frac{1}{1+\lambda}\frac{f_h'}{K_h} + \frac{\lambda}{1+\lambda}\frac{p_h}{\eta} \qquad (3)$$

We now examine the financial consequences of a switching from regime I to

$$p_s - c = \frac{1}{1+\lambda}\frac{f_s'}{K_s} + \frac{\lambda}{1+\lambda}\frac{p_s}{\eta}, \tag{4}$$

$$\lambda = \frac{r(K_h + nK_s) - \left[\frac{f_h'}{K_h}G + n\left(\frac{2f_h'}{K_h}+\frac{f_s'}{K_s}\right)D_s\right]}{[p_hG + n(2p_h+p_s)D_s]/\eta - r(K_h + nK_s)}$$

regime II. When there is little congestion in the spoke airports, i.e., f_s' is small compared with f_h',
equations (3) and (4) lead to the following inequality:

$$p_h - c > p_s - c > 0$$

Since the hub airport is subject to more congestion than the spoke airports, it must be the case that

$$\frac{D_h}{K_h} > \frac{D_s}{K_s}$$

Combining the above two inequalities gives

$$\frac{(p_h-c)D_h}{K_h} > \frac{(p_s-c)D_s}{K_s}. \tag{5}$$

On the other hand, the breakeven constraint can be stated as follows:

$$(p_h-c)D_h + n(p_s-c)D_s = r(K_h + nK_s)$$

Rearrange, we get

$$K_h\left[\frac{(p_h-c)D_h}{K_h} - r\right] = -nK_s\left[\frac{(p_s-c)D_s}{K_s} - r\right] \tag{6}$$

(5) and (6) imply that

$$p_h - c > \frac{rK_h}{D_h}, \quad and \quad p_s - c < \frac{rK_s}{D_s}$$

i.e., there will be financial surplus in the hub and deficit in the spoke airports. Therefore, a cross subsidy is necessary within the hub-spoke system.

4. IMPACT OF REGIME CHANGE ON OVERALL AIRPORT CHARGES

In the last section, we examined the second best pricing regime with an overall financial constraint. Now, we look at the consequences on the amount of total airport charges that an typical airline operating on the hub-and-spoke network will have to pay. It can be shown that, as the elasticity of demand is small, the price of using the hub airport will increase while the price of using the spoke airports will decrease under regime II, compared with regime I. Consequently, the traffic originating from the hub, G, will be reduced due to increased price, p_h. However, the effect of changing prices, caused by a regime change, on the traffic originating from the spoke airports is less clear because the change in traffic demands depends on change in prices of using both the hub and the spoke airports, namely, $2dp_h + dp_s$. Under the financial breakeven condition, the total net revenue from the hub-spoke system must remains zero, i.e.,

$$(p_h-c)(G+2nD_s) + n(p_s-c)D_s - r(K_h+nK_s) = 0$$

Differentiate,

$$Gdp_h + (p_h-c)dG + n(2dp_h+dp_s)D_s + n[2(p_h-c)+(p_s-c)]dD_s = 0$$

or

$$G\left[1 - \frac{p_h-c}{p_h}\eta\right]dp_h + nD_s\left[1 - \frac{2(p_h-c)+(p_s-c)}{2p_h+p_s}\eta\right](2dp_h+dp_s) = 0 \qquad (7)$$

Empirical finding that η is small suggests that

$$1 - \frac{p_h-c}{p_h}\eta > 0, \qquad 1 - \frac{2(p_h-c)+(p_s-c)}{2p_h+p_s}\eta > 0.$$

Hence, equation (7) implies that when $dp_h > 0$, it must be the case that $(2dp_h + dp_s)D_s < 0$, or $2dp_h + dp_s < 0$. This means that for transit fleights originating from the spoke airports, airlines are facing an overall reduction in airport charges. This also implies that $dD_s > 0$.

Next, we look at the change in total traffic volume as the result of a regime change.

$$\begin{aligned} dD_h+ndD_s &= dG+3ndD_s \\ &= -G\eta\frac{dp_h}{p_h} - 3nD_s\eta\frac{2dp_h+dp_s}{2p_h+p_s} \qquad (8) \\ &= -G\eta\frac{dp_h}{p_h}\left[1 + \frac{3nD_s}{G}\frac{(2dp_h+dp_s)/(2p_h+p_s)}{(dp_h/p_h)}\right] \end{aligned}$$

In the above equation, the first term is positive while the second term is negative. However, note that the change in total net revenue, dR, can be expressed as:

$$dR = G\left[1-\frac{p_h-c}{p_h}\eta\right]dp_h + nD_s\left[1 - \frac{2(p_h-c)+(p_s-c)}{2p_h+p_s}\eta\right](2dp_h+dp_s)$$

The financial breakeven condition implies that dR = 0, hence

$$\frac{(2dp_h+dp_s)/(2p_h+p_s)}{dp_h/p_h} = \frac{-\,G[(1-\eta)p_h+\eta c]}{nD_s[(1-\eta)(2p_h+p_s)+3\eta c]}$$

Substituting the above result into (8) leads to

$$\begin{aligned} dD_h+ndD_s &= -\eta G\frac{dp_h}{p_h}\left[1 - \frac{3(1-\eta)p_h+3\eta c}{(1-\eta)(2p_h+p_s)+3\eta c}\right] \\ &= \eta G\frac{dp_h}{p_h}\frac{(1-\eta)(p_h-p_s)}{(1-\eta)(2p_h+p_s)+3\eta c} \\ &> 0. \end{aligned}$$

That is, the total traffic volume of the hub-spoke system will increase in regime II.

Apparently, switching from regime I to regime II cannot be welfare reducing because the constraints used in regime I is a subset of regime II. Moreover, since the solution to regime I is not the optimal solution to regime II, switching from regime I to regime II must be stricly welfare enhancing.

5. CONCLUDING REMARKS

With the ever intensifying attempt by airlines to improve operational efficiency and expanding, or at least maintaining, market share in today's increasingly competitive market, the efficient hub-and-spoke networks have become vitally important to airlines' success. The hub-and-spoke airport networks allow the airlines to operate more efficienty, meanwhile providing travellers with better connection and more convenience. The trend is likely to extend beyond national boundaries in the future when the airline services become more and more globalized. However, the existing pricing policies discussed in the literature and/or used by various airport authorities have not recognized the interrelations among the air traffics originating from various points in a hub-and-spoke system. Neither first best nor second best pricing schemes which consider each airport in a hub-and-spoke network individually is truly socially optimal because they fail to take into account the externalities which exist if interconnection traffics are not treated explicitly.

This paper addresses the socially optimal pricing of airports taking the hub-and-spoke network as a system, recognizing that the traffic demand in spoke airports and in hub airports are complementary. We first investigated a hub-and-spoke airport system without financial constraint, then we examined the airport system with financial constraint. Comparing the results of imposing financial breakeven condition to the hub-and-spoke network as a system with imposing breadeven condition to each airport individually, we find that the system approach calls for a cross-subsidy within the airports in the system. Generally, congested hub airports should charge a higher price for the use of the airports and transfer its financial surplus to underutilized spoke airports to cover the deficits in the spoke airports. Relative to the optimal pricing concerning individual airports, the system approach is welfare enhancing. It is also found that under the new pricing scheme, a typical airline operating on the hub-and-spoke network would probabily face an overall reduction in total airport charges on an average fleight. Further, switching to the system optimization pricing scheme is likely to stimulate overall traffic volume.

The purpose of this paper is only to bring the issue up for further discussion. Admittedly, the models used in this paper are only illustrative and, therefore, are much simplified. There remain many problems with the designing and implementing socially optimal pricing scheme for the emerging hub-and-spoke airport networks. Nevertheless, we believe that the issue is of significant importance, both theoretically and practically, and deserves future research effort.

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