

Airport Pricing of Private Airports in an Asymmetric Hub–Spoke Network

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Airport Pricing of Private Airports in an Asymmetric Hub–Spoke Network¹⁾

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Abstract:

This paper examines the pricing strategy of private airports. To capture the relationship between airport fees and airport locations, we develop a model with the asymmetric hub-spoke network. We obtain the following results. First, spoke airports which are far from the hub set their airport fees low. Second, the hub airport offers a large discount for transit passengers when the average distance between the hub and spokes is long. Finally, when all cities possess the same population, the policy maker can improve social welfare by allowing the hub to discriminate transit passengers in the setting of airport fees.

Keywords: Airport Pricing, Hub–Spoke Network, Asymmetric Network, Price Discrimination

1. Introduction

After the liberalization in the aviation industry, the networks of airlines changed from the point-to-point to the hub-spoke design. As a result, passengers departing from airports at a spoke node (spoke airport) now have to transit at a hub when they travel. This transit at the hub imposes some additional costs on passengers from spoke airports. Therefore, transit passengers incur larger trip cost than those departing from hub airports. The cost related to the transit may include the airport fee payment; that is, transit passengers have to pay the airport fees at the departing spoke and hub airports. However, hub airport operators offer a discounted fee for transit passengers. Figure 1 summarizes the ratio of the discounted transit airport fee against the departing airport

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fee for the five largest airports in Europe in 2011: London Heathrow (LHR), Charles de Gaulle (CDG), Frankfurt (FRA), Amsterdam (AMS) and Madrid (MAD). In Figure 1, the degree of the discount differs among these five airports: LHR offers the highest transit fee, 82% of the departing fee, while MAD offers the lowest, 53% of the departing fee. Here, the fees include both airline fees (landing fees, noise charges and parking charges) and passenger fees (the Passenger Service Facility Charge (PSFC) and Passenger Security Service Charge (PSSC)). The object of discount is the latter.

The formation of the hub-spoke network may also affect the spoke airport fee. Figure 2 shows the relationship between the fee of European airports and the minimal distance to the five largest airports in Europe: LHR, CDG, FRA, AMS, and MAD. Each dot represents an European airport with more than one million passengers in 2011, while the bold line in Figure 2 represents the fitted line. The fitted line may suggest that the airport fee decreases as the minimal distance to the major hubs increases. This paper aims to clarify the mechanisms of the data presented in Figures 1 and 2; that is, (i) why do spoke airports, which are farther from the hubs, set their airport fees lower and (ii) what is the determinant of the discount rate for the transit passengers offered by hub airports?

<Figure1: HERE>

<Figure2: HERE>

Silva and Verhoef (2013), Silva et al. (2014), Pels and Verhoef (2004) and Czerny and Zhang (2015) examined welfare-maximizing public airports. These studies showed that optimised airport charges internalise congestion externalities and correct the inefficiency caused by airlines' market power exertion. However, research focused on private airports is needed because many airports all over the world, especially in the United Kingdom, have been privatised, or undergoing the process of privatisation. Focusing on the private airport setting, airport competition is the largest concern. Teraji and Morimoto (2014) explained the mechanism whereby airports in relatively small cities are chosen as hub airports by the model in which two airports compete for the hub position. Kawasaki (2014) studied price discrimination strategy of two competing airports. Czerny et al. (2013) focused on competition between two ports in two countries for demand in a third region. These studies have a problem in which they assume a symmetric network or focus only on one or two airports.

We develop the model with private airports in an asymmetric hub–spoke network to analyse how distance between the hub and spoke airports affects airport charges. In the model, spoke airports locate at an arbitrary distance from the hub and the number of spoke airports is also arbitrary.

The rest of this paper is organized as follows. In Section 2, we describe the model, which is used to clarify the reason why spoke airports that are farther from the hubs set their airport fees lower and what affects the discount rate for the transit passengers at hub airports. In Section 3, we solve the game among airports and compare the analytical results with some stylized facts described above. In Section 4, we derive the welfare effect for each spoke market and analyse how the distance to the hub affects the welfare loss of each market. In Section 5, we suggest the discriminatory pricing policy to improve the social welfare. Finally, Section 6 states concluding remarks.

2. The Model

Let us consider a situation in which an airline connects $S + 1$ airports with a foreign country by forming a hub-spoke network as shown in Figure 3.² In Figure 3, r_s represents the distance between the hub and each spoke s , and we normalize the distance between the hub and foreign country to 1. Hereafter, we refer to the hub airport as *Airport h* , each spoke airport as *Airport s* ($s = 1, 2, \dots, S$), and *City i* ($i = h$ and $1, 2, \dots, S$) is the city in which *Airport i* is located. The population of *City i* is represented by n_i and we normalize the population of *City h* to 1, $n_h = 1$.

² Long-haul flights from *Airport h* to the foreign county represent flights such as those from Europe to Asia or to the United States.

<Figure 3: HERE>

The economy has three agents: airports, airline, and consumers. The sequence of decisions among these agents is as follows. First, all airports set their airport fees simultaneously to maximize their revenue. Second, the airline sets its fares to maximize its profit. Finally, consumers in each city decide their demand for flights to the foreign country. Hereafter, we trace the decision-making process.

The demand for air services is

$$d_h = 1 - p_h - a_d \quad (1.1)$$

$$d_s = n_s (1 - p_s - a_t - a_s) \quad \text{for } s = 1, 2, \dots, S, \quad (1.2)$$

where p_i denotes the airfare. a_d and a_t denote the airport fees of the hub for the departing passengers and for the transit passengers, respectively. We call the former “departing fee” and the latter “transit fee.” In Eq. (1.2), a_s is the airport fee of a spoke airport. Hereafter, we refer to passengers departing from *Airport h* as “hub passengers” and passengers departing from *Airport s* as “spoke passengers.”

The airline creates the hub-spoke network and provides two types of flights, connecting flights between *Airport h* and each spoke airport, and direct flights between *Airport h* and the foreign country. We assume that the airline’s operating cost is proportional to the passenger-kilometer. Specifically, operating cost per passenger is c_k for the connecting flight and c for the direct flight. The total operating cost is

$$C = cd_h + \sum_{s=1}^S (1 + \gamma_s)cd_s. \quad (2)$$

The first term is the operating cost for shipping hub passengers and the second term is the operating cost for shipping spoke passengers. Here, we assume that the airline does not pay airport fees. In reality, while airlines pay airport fees such as landing, aircraft parking, and handling fees, they are shifted onto passengers through the airfare. Therefore, the equilibrium demand and social welfare are given just as functions of total airport fees (= the sum of all the fees levied by airport operators). Therefore, in our model, only passengers pay airport fees. Similar assumptions are used in Oum et al. (1996) and Kawasaki (2014).

Using (2), we obtain the airline's profit as

$$\pi = (p_h - c)d_h + \sum_{s=1}^S [p_s - (1 + \gamma_s)c]d_s. \quad (3)$$

The first term is the profit per hub passenger and the second term is the profit per spoke passenger. The airline sets its airfare p_i to maximize profit:

$$\max_{p_i} \pi.$$

We obtain airfares from the first-order conditions as follows:

$$p_h = \frac{1 + c - a_d}{2}, \quad (4.1)$$

$$p_s = \frac{1 + (1 + \gamma_s)c - a_t - a_s}{2}. \quad (4.2)$$

Substituting these two equations into (1), we rewrite the demand as a function of airport

fees, a_a , a_t , and a_s :

$$d_h = \frac{1 - c - a_a}{2}, \quad (5.1)$$

$$d_s = \frac{n_s [1 - (1 + \gamma_s)c - a_t - a_s]}{2}. \quad (5.2)$$

Each airport levies airport fees on passengers. Total fee revenue is computed as

$$R_h = a_a d_h + a_t \sum_{s=1}^S d_s, \quad (6.1)$$

$$R_s = a_s d_s. \quad (6.2)$$

The first term of (6.1) is the revenue from hub passengers and the second term is from spoke passengers. We ignore airports' operating cost; therefore, private airports set their airport fees to maximize their fee revenue, that is,

$$\max_{a_i, t_i} R_i.$$

3. Equilibrium

This section derives the equilibrium airport fees in the hub-spoke network. Furthermore, we verify the stylized facts given in Figures 1 and 2; specifically, whether the distance to the hub affects the airport fees of each spoke airport and whether the hub operator reduces its transit fee as the network size expands. In Subsection 3.1, we solve the game among airports, and Subsection 3.2 uses this solution to check if the two

stylized facts work in our setting.

3.1. Equilibrium Airport Fees

Solving each airport's revenue maximizing problem, we obtain the best reaction functions as follows:

$$a_d = \frac{1 - c}{2}, \quad (7.1)$$

$$a_t(a_1, \dots, a_s) = \frac{1 - c}{2} - \frac{1}{2} \left(c\bar{\gamma} + \frac{\sum_{s=1}^S a_s n_s}{\sum_{s=1}^S n_s} \right), \quad (7.2)$$

$$a_s(a_t) = \frac{1 - (1 + \gamma_s)c - a_t}{2}. \quad (7.3)$$

Here, $\bar{\gamma} \equiv \sum_{s=1}^S n_s \gamma_s / \sum_{s=1}^S n_s$ is the population-weighted average distance between the hub and spokes. See **appendix A** for the derivation of the best responses and equilibrium airport fees. According to (7), we obtain Lemma 1:

Lemma 1

The transit fee of the hub and the airport fee of spoke airports are strategic substitutes.

For spoke passengers, airport services at the hub and each spoke are complementary goods. Therefore, if one airport increases its fee, the other airport has to decrease its fee.

By solving (7), we obtain the equilibrium airport fees as

$$a_d = \frac{1 - c}{2}, \quad (7.1)$$

$$a_t = \frac{1 - (1 + \bar{\gamma})c}{3}, \quad (8.1)$$

$$a_s = \frac{1-c}{3} + \frac{1}{6}c(\bar{v} - 3\gamma_s). \quad (8.2)$$

3.2. Pricing strategies of private airports

In this subsection, we discuss pricing strategies by focusing on the distance. We start with airport fees of spoke airports. Hereafter, *Airport s'* is farther from the hub than *Airport s*, that is, $\gamma_{s'} > \gamma_s$. From (8.2), we obtain

$$\begin{aligned} a_s - a_{s'} &= \frac{c}{6}(\bar{v} - 3\gamma_s) - \frac{c}{6}(\bar{v} - 3\gamma_{s'}) \\ &= \frac{c}{2}(\gamma_{s'} - \gamma_s) > 0. \end{aligned}$$

This result is summarized in Proposition 1.

Proposition 1

Airport fees of the spoke airport decreases as the distance to the hub, γ_s , increases.

Demand for connecting flights decreases and becomes more elastic as the distance between a spoke airport and the hub increases because airfares become higher due to the airline's higher operating cost. Therefore, the spoke airport lowers its airport fee to boost demand. This result explains the fitted line in Figure 2. When the distance to the hub is long, the spoke airport chooses the lower airport fee, which offsets the higher airfare and increases the demand.

We move to pricing strategies of the hub airport and investigate the discount for transit passengers. According to (7.1) and (8.1), we obtain the ratio of the transit fee to

departing fee as follows:

$$\frac{a_t}{a_d} = \frac{2}{3} - \frac{2c}{3(1-c)} \bar{r}. \quad (9)$$

Differentiating (9) with respect to \bar{r} , we obtain Proposition 2.

Proposition 2

The ratio of the transit fee to the departing fee decreases as the weighted average distance, \bar{r} , increases.

The hub lowers its transit fee and compensates for higher airfare of spoke routes to attract more transit passengers when spoke airports are located far from the hub. On the other hand, the departing fee is independent from the location pattern of spoke airports. Therefore, the transit fee gets relatively small compared to the departing fee as the average distance becomes large. Note that in Figure 1, the discount ratio of MAD is the lowest among the five largest airports. This can be interpreted as follows. Since MAD locates at the fringe of Europe compared to the other four airports, the operator of MAD discounts the transit fee more than the others to attract more transit passengers from spoke airports.

4. Welfare Analysis

This section clarifies the effect of distance to the hub upon the social welfare for each spoke route. To deal with this problem, we designate *Route s* as the route from *Airport s*

to the foreign country via the hub. We define the social welfare for *Route s* as the gross consumer benefit minus the social cost.

$$W_s = \frac{1}{2} (1 + p_s + a_c + a_s) d_s - (1 + \gamma_s) c d_s. \quad (10)$$

The first term is the lower part of the inverse demand function and the second term is the operating cost. The social welfare in the equilibrium is

$$W_s^* = \frac{1}{288} (21X_s + Y)(3X_s - Y)n_s. \quad (11)$$

Here, $X_s = 1 - c - c\gamma_s$ and $Y = 1 - c - c\bar{\gamma}$.

At the optimum, airfare should be equal to the airline's marginal cost, and airport fees should be zero. Therefore, the social welfare in the optimum, W_s^o , is

$$W_s^o = \frac{1}{2} X_s^2 n_s. \quad (12)$$

See **Appendix B** for the derivation of these social welfare functions. The welfare loss is

$W_s^o - W_s^*$, and we define the welfare loss ratio on *Route s* as

$$\begin{aligned} \theta_s &\equiv \frac{W_s^o - W_s^*}{W_s^o} \\ &= \frac{1}{144} \left(81 + 18 \frac{Y}{X_s} + \frac{Y^2}{X_s^2} \right). \end{aligned} \quad (13)$$

This ratio indicates the degree of market distortion. A large θ_s means large welfare loss and large market distortion.

To analyze the relationship between the welfare loss and the distance, let us compare the two spoke airports, s and s' ($\gamma_{s'} > \gamma_s$). From (13), we can state

$$\theta_s - \theta_{s'} = \frac{1}{144} \left[18 \left(\frac{1}{X_s} - \frac{1}{X_{s'}} \right) Y + \left(\frac{1}{X_s^2} - \frac{1}{X_{s'}^2} \right) Y^2 \right] < 0.$$

Since, $\gamma_{s'} > \gamma_s$, then $X_{s'} = 1 - c - c\gamma_{s'} < X_s = 1 - c - c\gamma_s$: therefore, $\theta_s - \theta_{s'} < 0$. Summarizing this, we obtain Proposition 3.

Proposition 3

The welfare loss ratio, θ_s , increases as the distance between the hub and spoke, γ_s , increases.

<Figure 4: HERE>

This result is derived from the hub's transit fee which is identical for all transit passengers. To clarify this mechanism, we define the "Net Benefit of the First trip (NBF_s)" and the "Total Markup (TM_s)."
 NBF_s captures the net social gain of the first trip along *Route s*, which is computed as the highest willingness to pay (equal to unity) minus marginal cost of the flight operation, $(1 + \gamma_s)c$. That is, $NBF_s = 1 - (1 + \gamma_s)c$.

TM_s captures the aggregate private gains of the airline, the hub and *Airport s*: that is,

$$\begin{aligned} TM_s &= [p_s - (1 + \gamma_s)c] + a_c + a_s = \frac{1 + a_c + a_s - (1 + \gamma_s)c}{2} \\ &= \frac{1 - (1 + \bar{\gamma})c}{12} + \frac{9\{1 - (1 + \gamma_s)c\}}{12} = \frac{Y}{12} + \frac{9X_s}{12}. \end{aligned} \quad (14)$$

In Figure 4, the area CDE is the welfare loss and the area ABE is the social welfare in the optimum. Since the slope of the demand curve is unity, according to Figure 4, the welfare loss ratio is written as $\theta_s = (TM_s/NBF_s)^2$. While both TM_s and NBF_s are

decreasing in γ_s , the decrease of TM_s is less significant than NBF_s due to the identical transit fee at the hub. Therefore, θ_s is increasing in γ_s .

In this section, we analyzed social welfare for each route under the identical transit fee. Next, we evaluate the welfare effect of the “discriminatory fee scheme” under which the hub can set different transit fees for each route.

5. Discriminatory airport fee policy

Proposition 3 shows that the relative welfare loss is increasing with the distance to the hub due to the uniform transit fee at the hub. To avoid the welfare loss due to uniform pricing for transit passengers, we consider the case where the hub can set its transit fee for each spoke route separately according to the demand elasticity. We call this case “discriminatory fee case.” In this case, the hub’s revenue maximizing problem is reduced to maximize the fee revenue for each route. That is,

$$\max_{a_{t,s}} a_{t,s} d_s.$$

Here, $a_{t,s}$ is the transit fee for *Route s* passengers. The best response is

$$a_{t,s}(a_s) = \frac{1 - (1 + \gamma_s)c - a_s}{2}.$$

Using the spoke’s best response, (7.3), we obtain the transit fee as

$$a_{t,s}^d = a_s^d = \frac{1 - (1 + \gamma_s)c}{3}.$$

In the discriminatory fee scheme, TM_s^d is computed as:

$$TM_s^d = [p_s - (1 + \gamma_s)c] + a_{c,s}^d + a_s^d = \frac{5\{1 - (1 + \gamma_s)c\}}{6} = \frac{5X_s}{6}. \quad (15)$$

In contrast, the total markup under the uniform fee scheme, TM_s^u , is computed in Eq.

(14). In comparison of these two,

$$TM_s^u - TM_s^d = \frac{Y}{12} + \frac{9X_s}{12} - \frac{5X_s}{6} = \frac{c(\gamma_s - \bar{\gamma})}{12}.$$

This indicates that, for the routes where $\gamma_s > \bar{\gamma}$, the discriminatory fee scheme improves the economic welfare. This is because, in these routes, the discriminatory fee scheme results in the airport fee payments reduction³ and the lower total mark up. In contrast, due to the rise in the airport fee payments, the economic welfare of the routes for $\gamma_s < \bar{\gamma}$ is decreased when the discriminatory fee scheme is introduced.

Next, we focus on change in the welfare loss of the entire network. Because the welfare loss for each route is expressed as the triangle CDE in Figure 2, the loss for each is calculated as $n_s TM_s^2 / 2$. Aggregating the loss for all routes, the differential in the welfare loss of the entire network under the two alternative fee schemes is computed

³ The differentials in the fees incurred by transit passengers in two cases are computed as:

$$a_{c,s}^u - a_{c,s}^d = \frac{1}{3}(\gamma_s - \bar{\gamma})c,$$

$$a_s^u - a_s^d = \frac{1}{6}(\bar{\gamma} - \gamma_s)c.$$

Superscripts **u** and **d** indicates the uniform fee and the discriminatory fee cases, respectively. Also note that the fees under the uniform case (with the superscript **u**) are derived as in Eqs. (8).

as:⁴

$$\Delta WL = \sum_{s=1}^s \frac{n_s (TM_s^{a^2} - TM_s^{u^2})}{2}. \quad (16)$$

If this sign is negative, the discriminatory fee scheme is more efficient than the uniform scheme; that is, the discriminatory fee scheme improves the economic welfare. To obtain a clear result, we assume that all spoke cities have the same population, that is, $n \equiv n_1 = n_2 = \dots = n_s$. We rewrite Eq. (16) as:

$$\Delta SW = \frac{1}{288S} nc\sigma^2 > 0, \quad (17)$$

where σ^2 is the variance of γ_s [see Appendix C for derivation of Eq. (17)]. This result is summarised as follows:

Proposition 4

When all the spoke cities have an identical population size, the discriminatory fee scheme is more efficient than the uniform scheme in terms of the entire welfare.

As shown in Proposition 4, when all the spoke cities have an identical population size, the policy maker can improve social welfare by allowing airports to discriminate passengers in setting airport fees. However in reality, price discrimination is banned in many countries. For example, the EU Airport Charges Directive (2009/12/EC) prohibits

⁴ Since, under the two alternative fee schemes, the hub passengers incur an identical airfare and airport fee, the loss at the hub airport remains at the same level; therefore, we ignore the change in the loss at the hub.

differentiated fees to airlines using the same service. In the US, airports are compelled to offer same fees for same service by 2013 FAA's Policy Regarding Airport Rates and Charges. Since these restrictions harm social welfare, we suggest that the discriminatory fee scheme should be introduced based on our results.

6. Conclusion

In this study, we analyzed airport pricing in an asymmetric hub-spoke network and obtained three results. First, the airport fees of a spoke airport decreases as the distance to the hub increases. This is because the demand from the spoke airport gets relatively smaller as the distance between the spoke and the hub increases, due to the high operating cost and airfare. Second, the ratio of the transit fee to the departing fee diminishes as the weighted average distance increases. Demand of a spoke route is a decreasing function of the distance. Therefore, the hub lowers its transit fee in attempt to boost the demand for transit services when spoke airports locate farther than average from the hub. Third, the welfare loss ratio increases as the distance between the hub and spoke increases. The mark-up ratio of a long spoke route is large due to the identical transit fee. According to the large mark-up ratio, the welfare loss ratio also becomes large. Moreover, we showed the possibility that the discriminatory fee scheme improves

the social welfare.

We need to extend our model in two aspects. First, we should establish a multi-hub model. It is often observed that some large airports compete for hub positions. Such competitions lead to discounting of airport fees. Second, we should consider airport groups and alliances among airports. If some airports are in one group or operated by a parent company, airport operators try to maximize the total profit of their group or company.

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Appendix A: Derivation of best responses.

We differentiate (6.1) with respect to a_h and t_h , and the first order conditions for the revenue maximization problem are:

$$\frac{\partial R_h}{\partial a_d} = d_h + a_d \frac{\partial d_h}{\partial a_d} = 0, \quad (\text{A.1})$$

$$\frac{\partial R_h}{\partial a_t} = \sum_{s=1}^S d_s + a_t \sum_{s=1}^S \frac{\partial d_s}{\partial a_t} = 0. \quad (\text{A.2})$$

Here,

$$\frac{\partial d_h}{\partial a_d} = -\frac{1}{2}. \quad (\text{A.3})$$

We differentiate (6.2) with respect to the total fee, $\tau_s \equiv a_s + t_s$, and the first order condition is

$$\frac{\partial R_s}{\partial a_s} = d_s + a_s \frac{\partial d_s}{\partial a_s} = 0. \quad (\text{A.4})$$

Here,

$$\frac{\partial d_s}{\partial a_s} = \frac{\partial d_s}{\partial a_t} = -\frac{1}{2} n_s. \quad (\text{A.5})$$

We arrange (A.1), (A.2), and (A.5) for a_d , a_t , and a_s using (A.3) and (A.5) and obtain

$$a_d - \frac{1-c}{2} = 0, \quad (\text{A.6})$$

$$\frac{a_t}{2} \sum_{s=1}^S n_s + \sum_{s=1}^S \frac{a_s t_s}{2} - (1-c) \sum_{s=1}^S n_s + c \sum_{s=1}^S \gamma_s n_s = 0, \quad (\text{A.7})$$

$$a_c + a_s - \frac{1 - (1 + \gamma_s)c}{2} = 0. \quad (\text{A.8})$$

We delete t_h in (A.6) using (A.7) and obtain

$$a_c = \frac{1 - c}{2} - \frac{1}{2} \left(c\bar{\gamma} + \frac{\sum_{s=1}^S a_s n_s}{\sum_{s=1}^S n_s} \right). \quad (\text{A.9})$$

Here,

$$\bar{\gamma} \equiv \frac{\sum_{s=1}^S n_s \gamma_s}{\sum_{s=1}^S n_s}.$$

Solving (A.8) for a_s , we obtain

$$a_s = \frac{1 - (1 + \gamma_s)c - a_c}{2}. \quad (\text{A.10})$$

Appendix B: Derivation of social welfare

(i) The social welfare in the equilibrium

Plugging (1) into (11), we delete d_s and obtain

$$W_s^* = \left[\frac{1}{2} (1 + p_s + a_t + a_s) - (1 + \gamma_s)c \right] (1 - p_s - a_s - a_t) n_s. \quad (\text{B.1})$$

Plugging (4.2) into (B.1), we delete p_s and obtain

$$W_s^* = \frac{1}{8} [3 - 3(1 + \gamma_s)c + a_t + a_s] [1 - (1 + \gamma_s)c - a_t - a_s] n_s. \quad (\text{B.2})$$

Plugging (8.1) and (8.3) into (B.2), we delete a_t and a_s and obtain

$$\begin{aligned} W_s^* &= \frac{1}{288} (22 - 22c - 21\gamma_s c - \bar{\gamma}c) (2 - 2c - 3\gamma_s c + \bar{\gamma}c) n_s \\ &= \frac{1}{288} (21X_s + Y)(3X_s - Y) n_s. \end{aligned} \quad (\text{B.3})$$

Here, $X_s = 1 - c - c\gamma_s$ and $Y = 1 - c - c\bar{\gamma}$

(ii) The social welfare in the optimum condition

Conditions for the optimum are that airfare should be equal to the airline's marginal cost and that airport fees should be zero. Under these conditions,

$$\alpha_h^0 = t_h = \tau_s = 0, \quad (\text{B.4.1})$$

$$p_s^0 = (1 + \gamma_s)c. \quad (\text{B.4.2})$$

And then, the demand in the optimum is

$$d_s = n_s [1 - (1 + \gamma_s)c]. \quad (\text{B.4.3})$$

Plugging (B.4)s into (11), we obtain the welfare function in the optimum as

$$\begin{aligned} W_s^o &= \frac{1}{2}(1 - c - c\gamma_s)n_s \\ &= \frac{1}{2}X_s^2n_s. \end{aligned}$$

Appendix C: Comparison of two airport fee schemes

The difference of the social welfare under both schemes is

$$\begin{aligned}\Delta WL &= \frac{1}{2}n \sum_s [(TM_s^d)^2 - (TM_s^u)^2] \\ &= \frac{1}{2}n \sum_s (TM_s^d + TM_s^u)(TM_s^d - TM_s^u).\end{aligned}\quad (\text{C.1})$$

Here,

$$\begin{aligned}TM_s^d + TM_s^u &= \frac{1}{12}(20 - 20c - c\bar{\gamma} - c\gamma_s), \\ TM_s^d - TM_s^u &= \frac{1}{12}(\bar{\gamma} - \gamma_s).\end{aligned}$$

Substituting them into Eq. (C.1) and we obtain

$$\begin{aligned}\Delta WL &= \frac{1}{288}n \sum_s [(20 - 20c - c\bar{\gamma} - c\gamma_s)(\bar{\gamma} - \gamma_s)] \\ &= \frac{1}{288}n \sum_s [c\gamma_s^2 - 20(1-c)\gamma_s - c\bar{\gamma}^2 - 20(1-c)\bar{\gamma}] \\ &= \frac{1}{288}n \left[c \sum_s \gamma_s^2 - 20(1-c) \sum_s \gamma_s - Sc\bar{\gamma}^2 + 20S(1-c)\bar{\gamma} \right].\end{aligned}\quad (\text{C.2})$$

Because $n \equiv n_1 = n_2 = \dots = n_S$, we rewrite the weighted average distance as:

$$\bar{\gamma} = \frac{\sum_s \gamma_s}{S} \Leftrightarrow \sum_s \gamma_s = S\bar{\gamma}.$$

We simplify Eq. (C.2) as:

$$\begin{aligned}\Delta WL &= \frac{1}{288}n \left(c \sum_s \gamma_s^2 - Sc\bar{\gamma}^2 \right) \\ &= \frac{1}{288S}nc \left(\frac{\sum_s \gamma_s^2}{S} - \bar{\gamma}^2 \right) \\ &= \frac{1}{288S}nc\sigma^2 > 0,\end{aligned}$$

where $\sigma^2 \equiv \left(\frac{\sum_s \gamma_s^2}{S} - \bar{\gamma}^2 \right) > 0$ is the variance of γ_s .

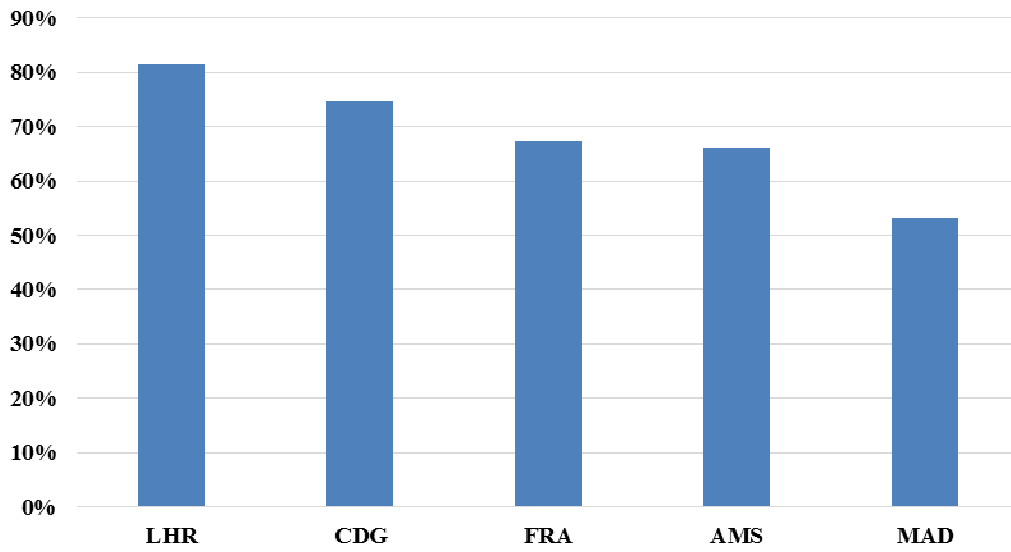


Figure 1: The ratio of the transit fee against the departing fee*

*This figure compares the fees of departing and transit passengers from a B787 passenger jet (280 seats). To compute the fees, we use the IATA Airport, ATC and Fuel Charges Monitor (IATA, 2013) and set several assumptions: the aircraft utilises the parking for three hours during the daytime; the loading factor is 71%; and the MTOW (Maximum Takeoff Weight) is 301 t.

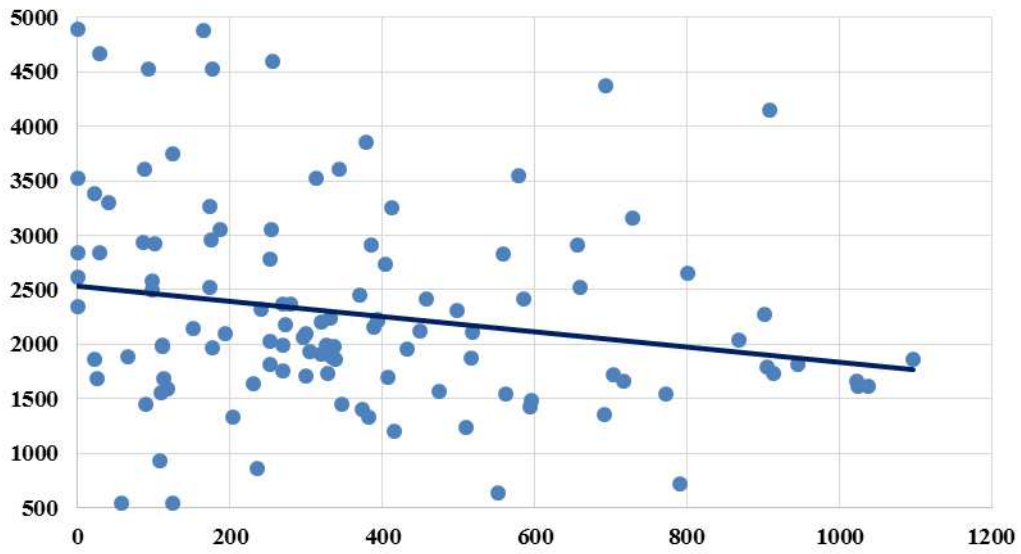


Figure 2: The relationship between the airport fee and the distance to the hub*

*: This figure demonstrates the departing fees for passengers boarding a B787 passenger jet (280 seats) for European international airports, which are appeared in the IATA Airport, ATC and Fuel Charges Monitor (IATA, 2013). In computing the airport charges, we set the same assumptions as in Figure 1.

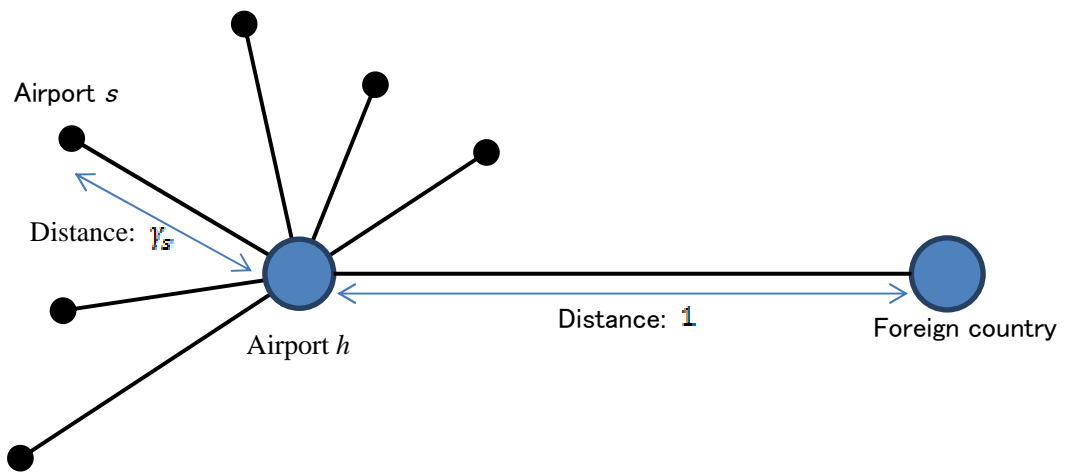


Figure 3: Hub-Spoke Network

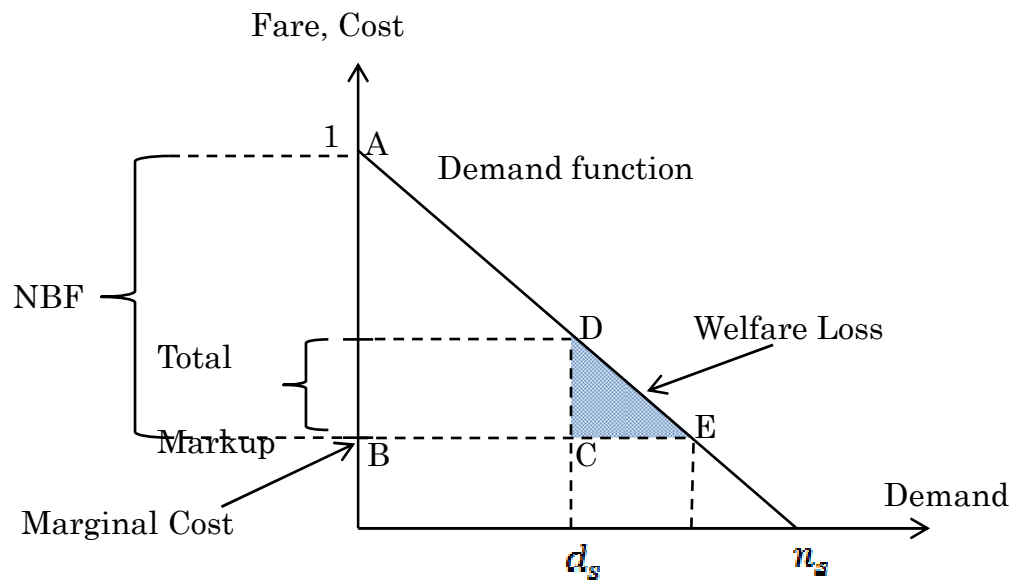


Figure 4: Welfare Loss for Route s