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Carrier collaboration with endogenous networks: Or, the limits of what carrier collaboration can achieve under antitrust immunity[1]

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Abstract

Airlines maintain complex networks that are to large extents complementary. Therefore, some passengers need to change aircraft and airlines to fly from their origin to their final destination. The present study captures pricing problems in terms of double marginalization but goes one step further by incorporating network choices. The model involves a two-stage game with two carriers who choose their complementary networks in the first stage and fares in the second stage. Each carrier's network involves one or two links that are distributed geographically or distributed in time. If both carriers maintain two links, then transfer passengers can choose between two alternative connections which they consider as imperfect substitutes. There are only transfer passengers, and maintaining a link is costly. The analysis reveals that carrier collaboration and antitrust immunity can eliminate double marginalization and create incentives to extend networks. Our results indicate that the scope for the improvement of carrier networks via antritrust immunity can be rather limited relative to the social desirability of more extensive carrier networks. A possible policy lesson is that airlines should be granted antitrust immunity conditional on network expansion and/or frequency obligations.
Keywords: Carriers; networks; frequencies; double marginalization; antitrust immunity; service obligations

1 Introduction

Airlines provide complex networks of flight links that are to large extents complementary. One reason for the complementarity is related to bilateral service agreements, which restrict the carriers' access to the national air space of foreign countries and their airports (for example, Czerny and Lang, 2019). Another reason are flight distances. If the flight distance is too long for a non-stop flight, the connection must be split into a combination of shorter flights. For instance, a flight from Australia or South America to Europe may be too long to fly non-stop. In this case, one flight could be operated by an Australian or South American airline, respectively, whereas the other flight could be operated by a European airline. Consider a passenger who wishes to fly from Sydney to Helsinki. This passenger may fly with Qantas from Sydney to Hong Kong, Singapore or Dubai and from there to Helsinki with Finnair. The complementarity implies that some passengers need to interline in the sense that they must change aircraft and carrier to fly from their origin to their final destination. Such complementarity raises the issue of a "chain of non-integrated concerns" as was highlighted by Spengler (1950). As a result, uncoordinated airline pricing leads to excessive fares via double marginalization (for example, Brueckner and Whalen, 2000).

Different forms of airline collaborations are common including codesharing and airline alliances (for example, Zhang and Czerny, 2012; Bilotkach, 2019). In the case of codesharing, airlines team up to jointly sell each others' seat capacities. Airline alliances go beyond the collaborative sale of seat capacity and also include other arrangements such as frequent flier program partnerships. Importantly for the present study, partner airlines are sometimes granted with antitrust immunity allowing them to jointly set fares to interline passengers so that double marginalization can be avoided.

The present study captures pricing problems in terms of double marginalization but goes one step further by incorporating scheduling problems in the form of route developments and/or frequency choices. The model involves a two-stage game with two carriers who choose their complementary networks in the first stage and fares in the second stage. Each carrier's network involves one or two links that are distributed geographically or distributed in time. If both carriers maintain two links, then transfer passengers can choose between two alternative connections which they consider as imperfect substitutes. There are only transfer passengers in the model, that is, non-stop passengers are absent. Maintaining a link is costly.

The study develops detailed insights on the relationship between carrier networks and the substitutability of the two alternative connections determined by a *differentiation parameter* which is part of the standard Dixit (1979) type of utility function. The analysis reveals that carrier collaboration and antitrust immunity can not only eliminate double marginalization but can further enhance the incentives to maintain two connections for interline passengers rather than one connection, both of which increases social welfare, depending on the value of the differentiation parameter.

To see that differentiation matters, consider the case of connections that are considered as perfect substitutes by interline passengers. In this case, maintaining two links can never, that is, neither for a profit-maximizing carrier nor for a welfare-maximizing carrier, be optimal because it increases maintenance costs without creating additional demands and benefits, respectively. The critical level of differentiation between routes that needs to be reached so that independent carriers would maintain two links in (the subgame-perfect) equilibrium is, however, higher than the corresponding level for collaborating carriers with antitrust immunity. In this sense, collaboration can create stronger incentives to maintain two connections for interline passengers. However, analytical results indicate that the scope for the improvement of carrier networks by collaboration and antitrust immunity can be rather limited relative to the social desirability of more complete carrier networks. This is because neither independent nor allied carriers consider consumer surplus gains in their network decisions. A possible policy lesson is that airlines should be granted antitrust immunity conditional on extending the network geographically and/or by increasing frequency supply.

Collaboration can increase the incentives to maintain a more extensive and complete network also through another channel. Even though the two routes would be sufficiently differentiated to support equilibrium networks with two connections, the perfect complementarity of carrier networks leads to the existence of a coordination problem in the sense that maintaining only one connection always represents an equilibrium network solution. Carrier collaboration can, therefore, support the maintenance of two connections by overcoming the potential coordination problem that exists in the case of independent network choices.

Bilotkach (2019) surveys papers on airline partnerships and antitrust immunity and distinguishes between studies which concentrate on price effects and studies which also consider non-price product characteristics. This paper contributes to the second type by analyzing how carrier collaboration can change network choices and how this can increase welfare depending on the heterogeneity of alternative connections. The paper most closely related to the present study is the one by Czerny et al. (2016). They consider a sequential structure in which the carriers choose frequencies and aircraft sizes in the first stage and fares in the second stage. They find that independent carriers strategically reduce frequency supply in the first stage in order to lower the other carrier's equilibrium fare in the second stage. In this case, carrier collaboration can increase frequency supply by eliminating the strategic reduction of frequencies by independent carriers, which is consistent with the results presented in this study. That carrier collaboration in the form of alliances can increase flight frequency in practice has been confirmed by Alderighi and Gaggero (2014). The present study contributes to this strand of the literature by highlighting that, besides the frequency interpretation, there is a geographical interpretation of the problem and by analyzing in detail the role of the heterogeneity between connections and the limited potential for collaboration and antitrust immunity to reach the welfare-optimal network structure. The study further contributes by highlighting the existence of a coordination problem.

The present study abstracts away from the issue of coordinating a given number of flights. This problem has been considered in a complementary study by Bilotkach (2007), who analyzes how carrier collaboration can help coordinating a given number of complementary flights. Adler and Hanany (2016) consider price and frequency choices in parallel carrier networks and find that carrier collaboration without antitrust immunity could be best for passengers. Alderighi and Gaggero (2018) empirically find a positive relationship between alliance membership and flight cancellations. Brueckner and Flores-Fillol (2020) consider endogenous pricing and frequency choices and provide a detailed discussion of how frequency choices can translate into schedule delays when carrier networks are complementary.

Many studies have theoretically and empirically highlighted the effects of carrier collaboration in the form of alliances and codeshares on air fares (for example, Oum et al., 1996; Park, 1997; Park and Zhang, 2000; Brueckner and Whalen, 2000; Brueckner, 2001 and 2003; Bamberger et al., 2004; Brueckner and Pels, 2005; Ito and Lee, 2005 and 2007; Whalen, 2007; Armantier and Richard, 2008; Gayle, 2008; Wan et al., 2009; Brueckner and Proost, 2010; Brueckner et al., 2011; Bilotkach and Hüschelrath, 2011, 2012 and 2013; Zou et al., 2011). Bilotkach (2005) and Zhang and Zhang (2006) analyze the rivalry between airline alliances. That carrier collaboration can reduce welfare by increasing air fares for non-stop passengers in complementary networks has been highlighted by Czerny (2009). Gaggero and Bartolini (2012) empirically analyze the determinants of airline alliances and provide insights on the airline incentives to join or form an alliance. The effect of carrier collaboration on the temporal profile of air fares has been studied by Alderighi et al. (2015). See Zhang and Czerny (2012) for a discussion of earlier studies of airline alliances and Bilotkach (2019) for a more recent overview over the corresponding literature and provides avenues for future research on the topic.

This paper is organized as follows. Section 2 presents the model. The demand functions depending on carrier network choices are derived in Section 3. Section 4 uses the demand functions to analyze best responses in terms of network choices and equilibrium network structures when carriers are independent and networks that maximize joint profits when carriers are allied. Section 4 further analyzes the effects of carrier collaboration on consumer surplus and welfare. Section 5 concludes and develops avenues for future research.

2 The Model

The model developed in this section, can have a geographical and a frequency interpretation. Consider the geographical interpretation first. This interpretation involves four airports denoted by A, H, J, and B, in which A could be Sydney airport, H Hong Kong airport, J Singapore airport and B Helsinki airport. Passengers wish to fly from airports A to B and from B to A. There are two carriers denoted by 1 and 2, which could be Qantas and Finnair, respectively. Each carrier maintains one or two links. For bilateral agreement and flight-distance reasons, carrier 1 can only maintain links between airports A and H and A and J, whereas carrier 2 can only maintain links between airports B and H as well as B and J. Thus, passenger flows between airports A and B require the two carriers to provide complementary links between these two airports. Hence, only when they both fly to airport J or when they both fly to airport H, then and only then they can serve passenger demand for flights between A and B. Networks in which transfers would not be feasible, for instance, carrier 1 maintains a link between A and J and carrier 2 maintains a link between H and B, are not considered in order to ensure that transfer passengers can exist. The cost of maintaining a link by, for instance, establishing a ground team at an airport is given by F. Per passenger-operating costs and airport charges are normalized to zero. Conditional on maintaining the links between airports i and j with $i, j = A, H, J, B$ and $j \neq i$, carriers charge fares denoted by p_{ij} for their services.

The three combinations of airline networks considered in the analysis are illustrated by Figure 1. Carrier 1's network is indicated by solid lines whereas carrier 2's network is indicated by dashed lines. Part (a) illustrates the full network in which each carrier maintains the maximum of two links. In this case, passengers can choose whether to transfer flights at airport H or airport J. Part (b) illustrates an asymmetric carrier network in which transfer is possible at airport H only. Part (c) illustrates a symmetric carrier network in which transfer is possible at airport H only.

Consider the frequency interpretation of this framework. This interpretation involves only one transfer airport but one or two links distributed in time. Frequency choices could, for instance, involve the decision about whether the carriers maintain only Monday flights versus maintaining Monday flights and Tuesday flights. Some passengers may have a preference for the Monday flight whereas others may have a preference for the Tuesday flight. An increase in the number of links and the corresponding increase in flight frequency can therefore reduce deviations of the passengers' preferred from the actual flight times and, thus, schedule delays (for example, Miller, 1972; Douglas and Miller, 1974). The following analysis will concentrate on the geographical interpretation to economize the language although the model also captures flight frequencies and therefore the results are more general than the geographical interpretation would suggest.

Denote the quantity of transfer passengers who transfer at airport H by q_H and the quantity of transfer passengers who transfer at airport J by q_J. In the case of perfectly complementary carrier networks of the kind displayed in 1, carrier collaboration would play no role for non-stop passengers. Therefore and to derive a better understanding of the fundamental drivers of carrier collaboration, the present study abstracts away from non-stop passengers. Passenger benefits, denoted by B, are of the Dixit (1979) type and given by

$$B(q_H, q_J) = a \cdot (q_H + q_J) - \frac{b}{2} \cdot \left(q_H^2 + q_J^2\right) - d \cdot q_H q_J \qquad (1)$$

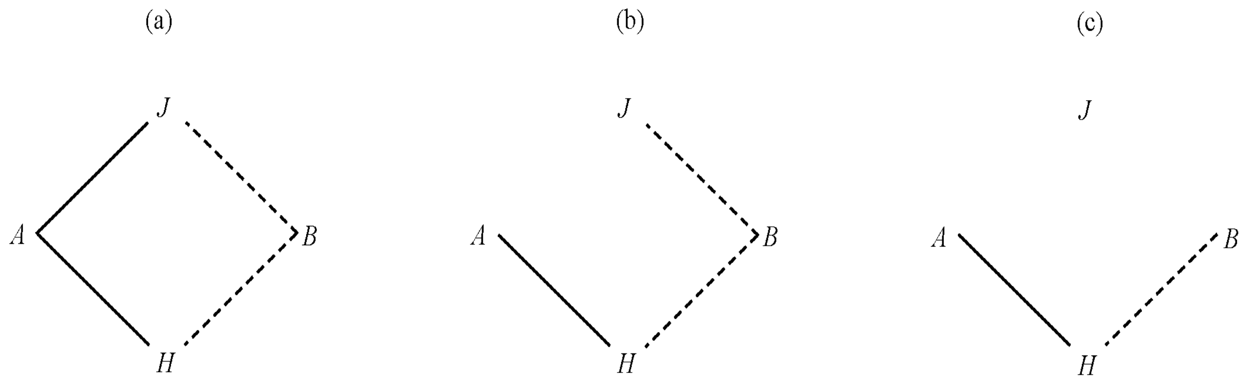

Figure 1: Carrier networks

with $a, b, d, b - d > 0$. Considering positive values of the differentiation parameter d implies that passengers consider transfers at airports H and J as imperfect substitutes. $b - d > 0$ implies that the cross-derivative $\partial^2 B/\partial q_H \partial q_J = -d$ is smaller in absolute values than the second derivatives $\partial^2 B/\partial q_i^2 = -b$ for $i = H, J$, which ensures the strict concavity of the benefit function in (1).

The differentiation parameter d is the parameter of interest, which will be used to derive a better understanding of how carrier collaboration can affect (complementary) networks in the case of substitute connections. To do this, the following compares the outcomes of scenarios with independent and allied carriers granted with antitrust immunity. The scenario of independent carriers is modelled as a two-stage game. In the first stage, carriers choose whether to maintain one or two links. In the second stage, carriers choose their fares for the maintained links to maximize their individual profits. The sequential time structure becomes immaterial in the case of allied carriers because carriers can, for instance, decide to jointly open a new connection by adding two links, which is not possible in the case of independent carriers. Therefore, the analysis of allied carriers can consider carriers who simultaneously choose fares and networks because the results carry over to the case of allied carriers and a sequential time structure.

3 Demand functions

Let δ_i denote an indicator variable that takes a value of one (that is, $\delta_i = 1$) if carrier i maintains one link and a value of two if carrier i maintains two links (that is, $\delta_i = 2$).

Two connections. Consider the case in which $\delta_1 = \delta_2 = 2$ and, thus, passengers can choose between transferring at airports H or J. To economize notation, let p_H denote the sum of prices paid by passengers who transfer at airport H, that is, $p_H = p_{AH} + p_{HB}$ and let p_J denote the sum of prices paid by passengers who transfer at airport J, that is, $p_J = p_{AJ} + p_{JB}$. The demands are determined by the equilibrium conditions

$$\frac{\partial B(q_H, q_J)}{\partial q_H} - p_H = a - bq_H - dq_J - p_H = 0 \tag{2}$$

and

$$\frac{\partial B(q_H, q_J)}{\partial q_J} - p_J = a - bq_J - dq_H - p_J = 0. \tag{3}$$

These conditions ensure that passengers will transfer at airports H and J if their benefits from traveling are not lower than the fares they have to pay for the two connections. Simultaneously solving the two equilibrium conditions in (2) and (3) yields the demand for transfer passengers at airport H, denoted by $D_H(p_H, p_J; \delta_1, \delta_2)$, and the demand for transfer passengers at airport J, denoted by $D_J(p_H, p_J; \delta_1, \delta_2)$ for $\delta_1 = \delta_2 = 2$. These demands can be written as

$$D_H(p_H, p_J; 2, 2) = \frac{1}{b^2 - d^2} \cdot (a(b - d) - bp_H + dp_J) \tag{4}$$

and

$$D_J(p_H, p_J; 2, 2) = \frac{1}{b^2 - d^2} \cdot (a(b - d) - bp_J + dp_H) \tag{5}$$

as long as fares are low enough to ensure that demands are non-negative. These demand functions imply that the demand for transfer passengers at airport i is decreasing in the fare p_i for $i = H, J$ and increasing in the fare p_j with $j \neq i$. The demand functions further imply that a simultaneous increase in fares p_H and p_J by the same amount reduces the transfer passengers' demands at both airports H and J. These are desirable properties of the demand functions.

One connection. Consider the case in which $\delta_1 = \delta_2 = 1$ and, thus, passengers can only transfer at airport H or airport J. Without loss of generality, assume that passengers transfer at airport H. The demand $D_H(p_H, p_J; 1, 1)$ is determined by the equilibrium condition

$$\frac{\partial B(q_H, 0)}{\partial q_H} - p_H = a - bq_H - p_H = 0 \tag{6}$$

leading to

$$D_H(p_H, p_J; 1, 1) = \frac{a - p_H}{b} \tag{7}$$

in which the right-hand side is decreasing in the price p_H for $p_H \leq a$.

Asymmetric case. Consider the case in which $\delta_j \neq \delta_i$ with $j \neq i$. This means that one carrier maintains one link whereas the other carrier maintains two links. Without loss of generality, assume that, in this case, carrier 1 maintains one link between A and H with $\delta_1 = 1$ whereas carrier 2 maintains two links with $\delta_2 = 2$. Despite that carrier 2 maintains two links, the perfect complementarity of carrier networks implies that passengers can only transfer at airport H because there is no service between airports A and J provided by carrier 1. Therefore, the demand function in the present asymmetric case can be described by the demand function which exists in the symmetric case with one feasible connection at airport H, that is, $D_H(p_H, p_J; 1, 2) = D_H(p_H, p_J; 1, 1)$.

4 Network Choices

Carrier 1's profit, denoted by π_1, depending on the number of passengers transferring at airports H and J, can be written as

$$\pi_1(p_H, p_J; \delta_1, \delta_2) = p_{AH} \cdot D_H(p_H, p_J; \delta_1, \delta_2) + p_{AJ} \cdot D_J(p_H, p_J; \delta_1, \delta_2) - \delta_1 F. \tag{8}$$

The first term on the right-hand side represents carrier 1's revenue from passengers transferring at airport H, whereas the second term represents the corresponding revenue from passengers transferring at airport J. The third term on the right-hand side represents the network maintenance costs, which can be equal to F or $2F$ depending on whether one or two links are maintained, respectively. Carrier 2's profit, denoted by π_2, depending on the number of passengers transferring at airports H and J, can analogously be written as

$$\pi_2(p_H, p_J; \delta_1, \delta_2) = p_{HB} \cdot D_H(p_H, p_J; \delta_1, \delta_2) + p_{JB} \cdot D_J(p_H, p_J; \delta_1, \delta_2) - \delta_2 F. \tag{9}$$

These profit functions can be used to derive the fares and networks in the subgame-perfect equilibrium when there are two independent carriers as well as the profit-maximizing set of fares and network when carriers form an alliance.

4.1 Independent carriers

Two connections. Consider the case of independent carriers in which both carriers maintain two links, that is, $\delta_1 = \delta_2 = 2$. Without loss of generality, the following concentrates on carrier 1. Carrier 1's profit depending on fares can be written as

$$\begin{aligned} \pi_1(p_H, p_J; 2, 2) &= p_{AH} \cdot D_H(p_H, p_J; 2, 2) + p_{AJ} \cdot D_J(p_H, p_J; 2, 2) - 2F & \text{(10a)} \\ &= \frac{1}{b^2 - d^2} \left((p_{AH} + p_{AJ})\, a\,(b-d) - p_{AH}\,(b p_H - d p_J) - p_{AJ}\,(b p_J - d p_H) \right) - 2F. & \text{(10b)} \end{aligned}$$

Carrier 1's best responses in terms of fares p_{Ai}, indicated by superscript br (hereafter best responses will be indicated by superscript br), are determined by the first-order conditions

$$\begin{aligned} \frac{\partial \pi_1(p_H, p_J; 2, 2)}{\partial p_{Ai}} &= D_i(p_H, p_J; 2, 2) + p_{Ai} \cdot \frac{\partial D_i(p_H, p_J; 2, 2)}{\partial p_i} + p_{Aj} \cdot \frac{\partial D_j(p_H, p_J; 2, 2)}{\partial p_i} & \text{(11a)} \\ &= \frac{1}{b^2 - d^2} \cdot \left(a\,(b-d) - b \cdot \left(2 p_{Ai}^{br} + p_{iB} \right) + d \cdot (2 p_{Aj} + p_{jB}) \right) = 0 & \text{(11b)} \end{aligned}$$

with $i = H, J$ and $j \neq i$. The third term on the right-hand side of (11a) exists and is positive in sign because transfer airports are considered as substitutes by passengers. This term indicates that carriers' best responses consider the positive effect of an increase in the charge on one link on the revenue obtained from maintaining the other link. Simultaneously solving the first-order conditions for carrier 1 in (11b) for $i = H, J$ yields best responses in terms of fares

$$p_{Ai}^{br}(p_{iB}) = \frac{a - p_{iB}}{2} \tag{12}$$

for $i = H, J$. These best responses are independent of the differentiation parameter and of the fares charged at the other connection and they are decreasing in the other carrier's fare for the complementary link on the same connection; thus, carrier fares on the same connection are strategic substitutes in the sense described by Bulow et al. (1985). Best responses are independent of the differentiation parameter because carriers internalize the effect of fares on the profits that can be generated from the other connection. Using symmetry, letting N denote the equilibrium fares (henceforth, equilibrium behaviors will always be indicated by superscript N) and solving for equilibrium fares leads to

$$p_{Ai}^{N} = p_{iB}^{N} = \frac{a}{3} \tag{13}$$

for $i = H, J$. This yields the well-known result that the sum of equilibrium fares, $p_{Ai}^{N} + p_{iB}^{N} = 2a/3$, exceeds monopoly fare, which is equal to $a/2$. Equilibrium fares are further independent of the differentiation parameter because best responses are independent of the differentiation parameter. Using equilibrium fares in (13) and letting p_i^N denote the sum of equilibrium fares $p_{Ai}^{N} + p_{iB}^{N}$, equilibrium profits can be written as

$$\pi_1(p_H^N, p_J^N; 2, 2) = \frac{2a^2}{9\,(b+d)} - 2F. \tag{14}$$

Whereas best responses and equilibrium fares are independent of the differentiation parameter, equilibrium profits are decreasing in the differentiation parameter, which is an artefact of the Dixit type of benefit functions because this functional form implies that an increase in the differentiation parameter reduces total market size.[1]

One connection. Consider the case of independent carriers in which both carriers maintain only one link and these links are connected. By assumption, passengers travel at airport H. Carrier 1's profit depending on fares can be written as

$$\pi_1(p_H; 1, 1) = p_{AH} \cdot D_H(p_H; 1, 1) - F \tag{15a}$$

$$= p_{AH} \frac{a - p_H}{b} - F. \tag{15b}$$

The first term on the right-hand side of (15a) shows that there is only one source of revenue whereas the second term shows that the maintenance cost is counted once. Carrier 1's best response in terms

[1] To see this, consider the demand functions in (4) and (5). Using symmetry in the sense that $p_H = p_J$, demand for passengers transfer at airport i can be written as $D_i = (a - p_i)\,/\,(b + d)$. This shows that market size is indeed decreasing in the differentiation parameter d. Levitan and Shubik (1971) provided a different demand functional form with an adjusted slope so that the aggregate demand is independent of the number of products or services in the market when prices are all equal. See Vives (1999) for a more detailed discussion on this funcitonal form. However, Levitan and Shubik's (1971) functional form does not include a differentiation-parameter that is independent of the number of products. Therefore, it is not considered in our analysis.

of the fare p_{AH} is determined by the first-order condition

$$\frac{\partial \pi_1(p_H;1,1)}{\partial p_{AH}} = D_H(p_H;1,1) + p_{AH} \cdot \frac{\partial D_H(p_H;1,1)}{\partial p_{AH}} \tag{16a}$$

$$= \frac{1}{b}\left(a - 2p_{AH}^{br} - p_{HB}\right) = 0. \tag{16b}$$

Solving the first-order condition for carrier 1 in (16b) yields the best response

$$p_{AH}^{br}(p_{HB}) = \frac{a - p_{HB}}{2}. \tag{17}$$

Thus, best response functions under one connection are identical to the best response functions for each connection in the case of two connections. Best responses are still decreasing in the other carrier's fare and therefore fares are strategic substitutes. Using symmetry and solving yields the equilibrium fares

$$p_{AH}^N = p_{HB}^N = \frac{a}{3}. \tag{18}$$

Again, the equilibrium fares under one connection are identical to the equilibrium fares for each link under two connections. This is not surprising given that the best responses are identical under one and two connections. Using equilibrium fares in (18), equilibrium profits can be written as

$$\pi_1(p_H^N;1,1) = \frac{a^2}{9b} - F. \tag{19}$$

Comparing the first terms on the right-hand sides of (14) and (19) shows that the average equilibrium revenue in the case of two connections is smaller than the equilibrium revenue in the case of one connection because the differentiation parameter d is positive by assumption. This implies that the presence of the differentiation parameter reduces the airlines' revenues by reducing the market size whereas it has no impact on the equilibrium fares. However, the total revenue still increases in the case of two connections if the differentiation parameter is small enough.

Asymmetric case. Consider the case of independent carriers in which carrier 1 maintains only one connection whereas carrier 2 maintains two connections. The perfect complementarity of carrier networks implies that there is no passenger transferring at airport J because there is no service between airports A and J provided by carrier 1. Passengers can only transfer at airport H, and demand in the asymmetric case is identical to the demand in the symmetric case with one connection, that is, $D_H(p_H, p_J; 1, 2) = D_H(p_H, p_J; 1, 1)$. Therefore, equilibrium fares in the asymmetric case are identical to the equilibrium fares in (18) which exist when both carriers maintain one connection, and the revenues are identical for these two cases too. The only difference between these two cases is that carrier 2 maintains one more connection between airports J and B and, thus, pays one more unit of maintenance cost given by F.

Equilibrium networks. The following assumption sets an upper limit on the maintenance costs F, which is to ensure that equilibrium profits are positive.

Assumption 1 *Maintenance costs are sufficiently low in the sense that*

$$F < \frac{a^2}{9(b+d)}. \tag{20}$$

An increase in the maximum reservation price a increases the market size whereas increases in the slope parameters b and d reduce market size. The right-hand side is therefore increasing in market size because it increases in a and decreasing in b and d, which is intuitive. Assumption 1 will henceforth be assumed to hold in the entire subsequent analysis.

The perfect complementarity between carrier networks implies that carriers cannot increase their own profit by unilaterally deviating from one to two connections. Therefore, if the other carrier maintains only one link, then maintaining two links can never be a best response.

Consider the case in which the other carrier maintains two links. To derive the best response in terms of networks, it is useful to consider the critical value of the differentiation parameter, denoted by d^I, for which the carrier would be indifferent between maintaining one or two links. To obtain the critical value of the differentiation parameter d^I, substitute d by d^I and equalize equilibrium profits in (14) and (19), which yields

$$\frac{2a^2}{9(b+d^I)} - 2F = \frac{a^2}{9b} - F. \tag{21}$$

Solving the equation for d^I yields the critical value of the differentiation parameter, which is given by

$$d^I = \frac{b\left(a^2 - 9bF\right)}{a^2 + 9bF}. \tag{22}$$

Because equilibrium profits in the case of two connections are decreasing in the differentiation parameter as shown in (14), maintaining two links can only be a best response if the differentiation parameter is small enough in the sense that $d \le d^I$. Altogether, this leads to the following best responses in terms of indicator variables:

$$\delta_i^{br}(\delta_j) = \begin{cases} 1 & \text{for} \quad \delta_j = 1 \\ 1 & \text{for} \quad \delta_j = 2 \text{ and } d \ge d^I \\ 2 & \text{for} \quad \delta_j = 2 \text{ and } d \le d^I \end{cases} \tag{23}$$

for $j \neq i$. These best responses imply the following equilibrium network constellations:

Lemma 1 *Consider independent carriers.*

(i) If $d > d^I$, then there exists one subgame-perfect Nash equilibrium in which both carriers maintain only one link, that is, $\delta_1^N = \delta_2^N = 1$.

(ii) If $d \leq d^I$, then there exist two subgame-perfect Nash equilibria in which both carriers either maintain only one link, that is, $\delta_1^N = \delta_2^N = 1$, or both carriers maintain two links, that is, $\delta_1^N = \delta_2^N = 2$ in which the latter Pareto dominates the former.

This lemma implies that maintaining one connection always represents an equilibrium network solutions whereas an equilibrium network with two connections exists only if the differentiation parameter is sufficiently small.

4.2 Allied carriers

If the two carriers form an alliance, then they behave as one company and collaboratively choose their networks and fares to maximize their joint profit. This reflects a situation in which carriers are granted antitrust immunity. In reality, many carriers are granted antitrust immunity in the case of complementary networks of the complementary types displayed in Figure 1. In this scenario, the sequential time structure becomes immaterial. Therefore, the analysis of allied carriers considers a simultaneously choice of fares and networks.

The total profits are denoted by π with $\pi = \pi_1 + \pi_2$. For $\delta_1 = \delta_2 = 2$ and $\delta_1 = \delta_2 = 1$, total profits can be written as

$$\pi(p_H, p_J; 2, 2) = p_H \cdot D_H(p_H, p_J; 2, 2) + p_J \cdot D_J(p_H, p_J; 2, 2) - 4F \tag{24a}$$

$$= \frac{1}{b^2 - d^2} \left(a\,(b-d)\,(p_H + p_J) - b\left(p_H^2 + p_J^2\right) + 2dp_Hp_J \right) - 4F \tag{24b}$$

and

$$\pi(p_H; 1, 1) = p_H \cdot D_H(p_H; 1, 1) - 2F \tag{25a}$$

$$= p_H \frac{a - p_H}{b} - 2F, \tag{25b}$$

respectively.

Allied carriers maximize their total profit by the choice of the (total) fares p_H and p_J. Let superscript A denote the profit-maximizing behaviors of allied carriers in terms of fares and networks. In the case of two connections, allied fares are determined by the first-order conditions

$$\frac{\partial \pi(p_H^A, p_J^A; 2, 2)}{\partial p_H} = \frac{\partial \pi(p_H^A, p_J^A; 2, 2)}{\partial p_J} \tag{26a}$$

$$= D_i(p_H^A, p_J^A; 2, 2) + p_i^A \cdot \frac{\partial D_i(p_H^A, p_J^A; 2, 2)}{\partial p_i} + p_j^A \cdot \frac{\partial D_j(p_H^A, p_J^A; 2, 2)}{\partial p_i} \tag{26b}$$

$$= \frac{1}{b^2 - d^2} \cdot \left(a\,(b-d) - 2bp_i^A - (b-d)\,p_j^A \right) = 0 \tag{26c}$$

with $i = H, J$ and $j \neq i$. Comparing the second and third terms on the right-hand sides of (11a) and (26b), respectively, shows that allied carriers consider each other's profit rather than only their own as would be the case with independent carriers which eliminates double marginalization. This is because the fares p_i and p_j reflect to the total fares rather than the individual carriers' fares.

In the case of one connection, the allied fare is determined by the first-order condition

$$\frac{\partial \pi(p_H^A;1,1)}{\partial p_H} = D_H(p_H^A;1,1) + p_H^A \cdot \frac{\partial D_H(p_H^A;1,1)}{\partial p_H} \tag{27a}$$

$$= \frac{a - 2p_H^A}{b} = 0. \tag{27b}$$

Comparing the second terms on the right-hand sides of (16a) and (27a) shows again that allied carriers consider each other's profit rather than only their own as would be the case with independent carriers which eliminates double marginalization.

Simultaneously solving the first-order conditions yields the profit-maximizing (total) fares of allied carriers, which are given by

$$p_i^A = \frac{a}{2} \tag{28}$$

for $\delta_1 = \delta_2 = 1$ and $\delta_1 = \delta_2 = 2$. Fares are independent of the network structure because the monopoly fares are determined by the semi-price elasticities of the demand functions, which depend on the maximum-reservation price a but not the demand slopes. Using these profit-maximizing fares, total profits in the cases of two connections and one connection can be written as

$$\pi(p_H^A, p_J^A; 2, 2) = \frac{a^2}{2\,(b+d)} - 4F \tag{29}$$

and

$$\pi(p_H^A;1,1) = \frac{a^2}{4b} - 2F, \tag{30}$$

respectively. Comparing the right-hand sides in (29) and (30) shows that the average equilibrium profit in the case of two connections is smaller than the equilibrium profit in the case of one connection because the differentiation parameter d is positive by assumption. This implies that the presence of the differentiation parameter reduces the airline's profits only by reducing the market size because it has no impact on the equilibrium fares.

Under Assumption 1, $F < \frac{a^2}{9(b+d)}$ and thus $F < \frac{a^2}{8(b+d)}$ implying that the right-hand side of (29) is strictly positive. Therefore, Assumption 1 ensures that equilibrium profits are positive both in the cases of independent and allied carriers.

Comparing equilibrium profits in (29) and (30) reveals:

Lemma 2 *Consider allied carriers. There is a critical value of the differentiation parameter, denoted by d^A with*

$$d^A \equiv \frac{b\left(a^2 - 8bF\right)}{a^2 + 8bF} \tag{31}$$

and $d^A > d^I$, such that:

(i) if $d \geq d^A$, then carriers maintain one connection, that is, $\delta_1^A = \delta_2^A = 1$, whereas

(ii) if $d \leq d^A$, then carriers maintain two connections, that is, $\delta_1^A = \delta_2^A = 2$.

Lemma 2 shows that the critical value of the differentiation parameter is larger for allied carriers than for independent carriers, that is, $d^A > d^I$. In this sense allied carriers are more inclined to maintain two connections than the independent carriers. This is because the allied carriers are collaborating and thereby eliminate double marginalization, which helps to better exploit the revenue opportunities arising from the maintenance of two connections relative to the revenues that could be obtained from maintaining only one connection.

Comparing the profits with allied carriers and independent carriers in the case of two connections and one connection respectively shows that profits of allied carriers are always higher than those of independent carriers. The reason is, again, the elimination of double marginalization under allied carriers. The network implications are more complex and can be described as follows:

Proposition 1 *The relationship between the networks of independent or allied carriers can be characterized as:*

(i) If $d \leq d^I$, there is a coordination problem in the sense that the networks of allied carriers may or may not be identical to the equilibrium networks of independent carriers.

(ii) If $d \in \left(d^I, d^A\right)$, then there is a discrepancy between the networks of allied carriers and equilibrium networks of independent carriers in the sense that allied carriers will maintain two connections whereas independent carriers will maintain only one connection in equilibrium.

(iii) If $d \geq d^I$, the networks of allied carriers are identical to the equilibrium networks of independent carriers.

Proposition 1 shows that allied carriers can change networks in two ways relative to independent carriers. First, for $d \in \left(d^I, d^A\right)$, collaboration stimulates the maintenance of the two-connection network. Considering the frequency interpretation of the present model, this theoretical finding is consistent with the results derived by Czerny et al. (2016) who found that carrier collaboration increases frequency supply and the empirical findings by Alderighi and Gaggero (2014) who also found that carrier collaboration increases frequency. Second, for $d > d^I$ collaboration can solve the coordination problem of independent carriers because independent carriers may stick to the one-connection network despite the fact that the two-connection network would be more profitable for them. This is because of the absence of a unique subgame-perfect equilibrium under this parameter condition.

4.3 Consumer surplus and welfare implications

Passengers only pay the fare, that is, there is no congestion costs or other costs involved. Therefore, consumer surplus, denoted by CS, is the difference between the benefits of travelling and the total payment to the airlines and given by

$$CS(q_H, q_J) = B(q_H, q_J) - p_H q_H - p_J q_J. \tag{32}$$

Substituting passenger quantities by their demand functions yields the consumer surplus depending on fares and networks, which can be written as

$$\begin{aligned} CS(p_H, p_J; \delta_1, \delta_2) \quad &= \quad B(D_H(p_H, p_J; \delta_1, \delta_2), D_J(p_H, p_J; \delta_1, \delta_2)) \\ &\qquad - p_H \cdot D_H(p_H, p_J; \delta_1, \delta_2) - p_J \cdot D_J(p_H, p_J; \delta_1, \delta_2). \end{aligned} \tag{33}$$

Concentrating on the symmetric cases with $\delta_1 = \delta_2 = 2$ and $\delta_1 = \delta_2 = 1$, consumer surplus depending on prices can be written as

$$CS(p_H, p_J; 2, 2) = \frac{1}{2\left(b^2 - d^2\right)} \left(2a^2\left(b - d\right) - 2a\left(b - d\right)\left(p_H + p_J\right) + b\left(p_H^2 + p_J^2\right) - 2dp_H p_J\right) \tag{34}$$

and

$$CS(p_H; 1, 1) = \frac{1}{2b}\left(a - p_H\right)^2, \tag{35}$$

respectively. For given fares, passengers always prefer to have two connections relative to one connection because it provides them with the possibility to choose between two differentiated services whereas such a choice would not be available carriers maintain only one connection. This directly implies:

Lemma 3 *For any given set of fares p_H and p_J, consumer surplus is always higher when carriers maintain two connection than when they maintain one connection, that is, $CS(p_H, p_J; 2, 2) \geq CS(p_H; 1, 1)$.*

Operating costs and airport charges are normalized to zero by assumption. The only cost is a fixed maintenance cost for each connection. Let W denote the welfare, which is the sum of consumer surplus and total profit and can be written as

$$W(p_H, p_J; \delta_1, \delta_2) \quad = \quad CS(p_H, p_J; \delta_1, \delta_2) + \pi(p_H, p_J; \delta_1, \delta_2) \tag{36a}$$

$$\quad = \quad B(D_H(p_H, p_J; \delta_1, \delta_2), D_J(p_H, p_J; \delta_1, \delta_2)) - (\delta_1 + \delta_2)\, F \tag{36b}$$

Welfares in the cases of two connections and one connection can be written as

$$W(p_H, p_J; 2, 2) = \frac{1}{2\left(b^2 - d^2\right)} \left(2a^2\left(b - d\right) - b\left(p_H^2 + p_J^2\right) + 2dp_H p_J\right) - 4F \tag{37a}$$

and

$$W(p_H; 1, 1) = \frac{1}{2b}\left(a^2 - p_H^2\right) - 2F, \tag{38a}$$

respectively.

Because passenger costs are normalized to zero, the first-best welfare is obtained when the fare is equal to zero. The reason is that a positive fare discourages passengers from flying although their benefits from flying would be positive. The first-best welfare in the cases of two connections and one connection can be written as

$$W(0,0;2,2) = \frac{a^2}{b+d} - 2F \tag{39}$$

and

$$W(0;1,1) = \frac{a^2}{2b} - F, \tag{40}$$

respectively.

Let superscript W denote the first-best behavior. Comparing welfares in (39) and (40) reveals:

Lemma 4 *There is a critical value of the differentiation parameter, denoted by d^W with*

$$d^W = \frac{b\left(a^2 - 2bF\right)}{a^2 + 2bF} \tag{41}$$

and $d^W > d^A > d^I$, such that:

(i) if $d \geq d^W$, then welfare is maximized when carriers maintain one connection, that is, $\delta_1^W = \delta_2^W = 1$, whereas

(ii) if $d \leq d^W$, then carriers maintain two connections, that is, $\delta_1^W = \delta_2^W = 2$.

The first-best welfare in the case of two connections is decreasing in the differentiation parameter as shown in (39). This implies that if the differentiation parameter is high in the sense that $d \geq d^W$, the extra welfare achieved by maintaining the second connection will be equal to or even smaller than the extra maintenance cost. Maintaining two connections reduces the total welfare relative to maintaining only one connection under these parameter conditions. Therefore, it is not useful from the welfare viewpoint to maintain two connections if these connections are close substitutes because the welfare gain from letting passengers choose their preferred connection is small relative to the maintenance costs in this case.

Consider the total welfare for independent carriers depending on networks. Using the equilibrium fares $p_H^N = p_J^N = p_{Ai}^N + p_{iB}^N = 2a/3$, which are equal in the cases of two connections and one connection, the equilibrium welfares $W(p_H^N, p_J^N; 2,2)$ and $W(p_H^N; 1,1)$ can be written as

$$W(p_H^N, p_J^N; 2,2) = \frac{10a^2}{9(b+d)} - 4F \tag{42}$$

and

$$W(p_H^N; 1,1) = \frac{5a^2}{9b} - 2F, \tag{43}$$

respectively. Given Assumption 1, both $W(p_H^N, p_J^N; 2,2)$ and $W(p_H^N; 1,1)$ are positive.

Let superscript IW indicate the welfare-maximizing network choices under independent carriers' equilibrium pricing behavior. Comparing equilibrium welfares in (42) and (43) reveals:

Objective function	Independent carriers	Allied carriers	First-best
Profit	d^I	d^A	-
Welfare	d^{IW}	d^{AW}	d^W

Table 1: Critical values of the differentiation-parameter

Lemma 5 *Consider independent carriers. There is a critical value of the differentiation parameter, denoted by* d^{IW} *with*

$$d^{IW} \equiv \frac{b\left(5a^2 - 18bF\right)}{5a^2 + 18bF}, \tag{44}$$

$d^{IW} > d^A > d^I$, *and* $d^{IW} < d^W$, *such that:*

(i) if $d \geq d^{IW}$, *then welfare is maximized when carriers maintain one connection, that is,* $\delta_1^{IW} = \delta_2^{IW} = 1$, *whereas*

(ii) if $d \leq d^{IW}$, *then carriers maintain two connections, that is,* $\delta_1^{IW} = \delta_2^{IW} = 2$.

Consider the welfare for allied carriers in the case of two connections and one connection. Using the profit-maximizing prices $p_H^A = p_J^A = a/2$, which are identical in the cases of two connections and one connection, the welfares $W(p_H^A, p_J^A; 2, 2)$ and $W(p_H^A; 1, 1)$ achieved by allied carriers can be written as

$$W(p_H^A, p_J^A; 2, 2) = \frac{3a^2}{2(b+d)} - 4F \tag{45}$$

and

$$W(p_H^A; 1, 1) = \frac{3a^2}{4b} - 2F, \tag{46}$$

respectively. Given Assumption 1, both $W(p_H^A, p_J^A; 2, 2)$ and $W(p_H^A; 1, 1)$ are positive.

Let superscript AW indicate the welfare-maximizing network choices under allied carriers' pricing behavior. Comparing welfares in (45) and (46) reveals:

Lemma 6 *Consider allied carriers. There is a critical value of the differentiation parameter, denoted by* d^{AW} *with*

$$d^{AW} \equiv \frac{b\left(3a^2 - 8bF\right)}{3a^2 + 8bF}, \tag{47}$$

$d^{AW} > d^{IW} > d^A > d^I$, *and* $d^{AW} < d^W$, *such that:*

(i) if $d \geq d^{AW}$, *then welfare is maximized when carriers maintain one connection, that is,* $\delta_1^{AW} = \delta_2^{AW} = 1$, *whereas*

(ii) if $d \leq d^{AW}$, *then carriers maintain two connections, that is,* $\delta_1^{AW} = \delta_2^{AW} = 2$.

Table 1 summarizes the five critical values of differentiation parameter in Lemmas 1, 2, 4, 5 and 6. Specifically, Lemma 6 implies the following unambiguous relationships:

$$d^I < d^A < d^{IW} < d^{AW} < d^W. \tag{48}$$

Thus, if the carriers are indifferent between one or two connections, then the welfare-maximizer prefers two connections in the sense that $d^I < d^{IW}$ and $d^A < d^{AW}$ independent of whether carriers are independent or allied. This is because fares are identical both in the case of two connections and one connection but consumer surplus, which carriers ignore, is higher in the case of two connections as highlighted by Lemma 3. Altogether,

Proposition 2 *From the welfare-viewpoint, both independent and allied carriers are too reluctant to maintain two connections in the sense that* $d^i < d^{iW} < d^W$ *for* $i = I, A$.

This is an important policy insight because it highlights that while carrier collaboration and antitrust immunity can enhance carrier networks (and pricing) there still remains room for further improvements in carrier networks from the welfare viewpoint. The discrepancy in network choices emerges because carriers ignore the increase in consumer surplus associated with two connections relative to one connection.

Figure 2 displays the relationship between the critical value of the differentiation parameter and the maintenance cost. The five curves from top to bottom display the critical differentiation parameter values d^W, d^{AW}, d^{IW}, d^A and d^I, respectively. All curves are depicted by solid lines except d^{IW} which is depicted by a dotted line. This figure can be used to derive insights about the potential welfare gains via network improvements through carrier collaboration and the limits of what carrier collaboration can achieve under antitrust immunity. Consider a move from independent to allied carriers. This move would lead to a network expansion for parameter constellations covered by the dark gray area (displaying the differences between d^A and d^I) whereas it would not lead to a network expansion for parameter constellations covered by the light gray area (displaying the differences between d^{AW} and d^A). The problematic cases are covered by the light gray area involving parameter constellations for which it would be desirable from the welfare viewpoint to have two connections but where even allied carriers stick to one connection. Comparing area sizes shows that the dark gray area is much smaller than the light gray area. This illustrates that the network improvements that can be achieved by carrier collaboration are rather limited. A policy lesson could be to combine antitrust immunity for allied carriers with services obligations schemes for specific connections that otherwise would remain shut or, considering the frequency interpretation of the framework, frequency obligations schemes to reduce schedule delays.

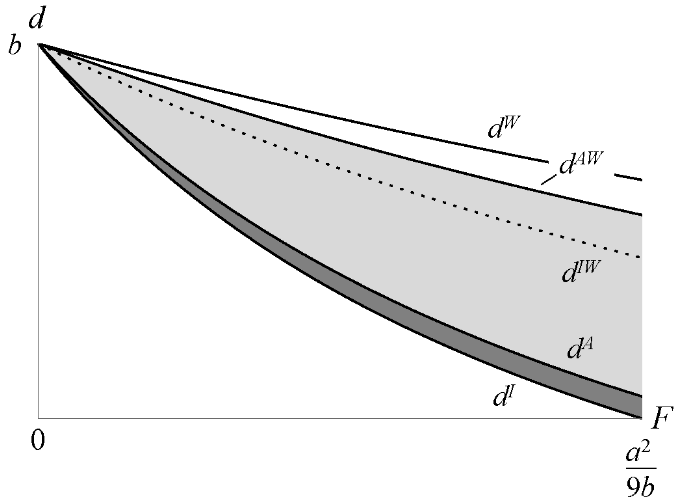

Figure 2: Critical regions of parameter values d and F

5 Conclusions

This study considered two carriers with perfectly complementary networks in which carrier networks maintain only one connection for transfer passengers or two alternative connections. There are only transfer passengers, and if carriers maintain two connections those are considered as imperfect substitutes by passengers. Carriers may act independently or collaboratively choose fares and networks. The latter is called the case of allied carriers with antitrust immunity. In the case of independent carriers, carriers independently choose their networks in the first stage by anticipating second stage-equilibrium prices.

The study showed that although allied carriers are more inclined to expand networks and/or increase frequency supply than independent carriers, substantial discrepancies between the network choices of allied carriers and the corresponding choices from the welfare viewpoint remain even if antitrust immunity is granted to collaborating carriers. The policy lesson is to combine antitrust immunity for allied carriers with services and/or frequency obligations schemes.

There are several avenues for future research. One would involve the consideration of more complex and realistic networks. There are many real-world cases in which carrier networks are overlapping in the sense that several carriers compete with each other because they maintain the same links in parallel. Extending the present model framework by capturing such overlapping network parts would be interesting and useful. Another useful and interesting extension would involve the consideration of non-stop passengers in addition to transfer passengers. Finally, it would be useful to capture economies of density (Caves et al., 1984). Higher passenger densities usually allow using, for instance, bigger and more fuel efficient aircraft, which reduces unit costs. This is relevant because the presence of economies of density creates incentives for carriers to concentrate passengers on certain links by reducing the number of links even though connections are considered as imperfect substitutes.

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Appendix

A Proofs

A.1 Proof of Lemma 1

If both carriers maintain one link, the best responses in (23) are mutually consistent in the sense that $\delta_i^{br}(\delta_j^{br}(1)) = 1$ for $j \neq i$, which is independent of the value of the differentiation parameter; thus, maintaining only one link represents an equilibrium network solution independent of the value of the differentiation parameter. If the other carrier maintains two links, best responses are mutually consistent in the sense that $\delta_i^{br}(\delta_j^{br}(2)) = 2$ for $j \neq i$ only if $d \leq d^I$; thus, maintaining two links represents an equilibrium network solution only if the differentiation parameter is small enough in the sense that $d \leq d^I$. Carriers can unilaterally shut down one link and force all passengers to use the one remaining connection, which would save maintenance costs. If maintaining the two connections is an equilibrium solution, maintaining two links rather than one link must be Pareto dominant because otherwise it could not be an equilibrium solution (because carriers can unilaterally shut down one connection). Altogether, this proves the results mentioned in parts (i) and (ii).

A.2 Proof of Lemma 2

To obtain the critical value of the differentiation parameter d^A, substituting d with d^A and equalizing equilibrium profits in (29) to (30) yields

$$\frac{a^2}{4\left(b + d^A\right)} - 2F = \frac{a^2}{8b} - F. \tag{a.1}$$

Solving the equation yields the critical value of the differentiation parameter, which is given by

$$d^A = \frac{b\left(a^2 - 8bF\right)}{a^2 + 8bF}. \tag{a.2}$$

The difference between d^A and d^I is given by

$$d^A - d^I = \frac{b\left(a^2 - 8bF\right)}{a^2 + 8bF} - \frac{b\left(a^2 - 9bF\right)}{a^2 + 9bF} \tag{a.3a}$$

$$= \frac{2Fa^2b^2}{72F^2b^2 + 17Fa^2b + a^4} \tag{a.3b}$$

which is positive.

A.3 Proof of Lemma 4

To obtain the critical value of the differentiation parameter d^W, substituting d with d^W and equalizing first-best welfare in (39) and (40) yields

$$\frac{a^2}{b + d^W} - 2F = \frac{a^2}{2b} - F. \tag{a.4}$$

Solving the equation yields the critical value of the differentiation parameter, which is given by

$$d^W = \frac{b\left(a^2 - 2bF\right)}{a^2 + 2bF}.$$

The difference between d^W and d^A is given by

$$d^W - d^A = \frac{b\left(a^2 - 2bF\right)}{a^2 + 2bF} - \frac{b\left(a^2 - 8bF\right)}{a^2 + 8bF} \tag{a.5a}$$

$$= \frac{12Fa^2b^2}{16F^2b^2 + 10Fa^2b + a^4} \tag{a.5b}$$

which is positive.

A.4 Proof of Lemma 5

To obtain the critical value of the differentiation parameter d^{IW}, substituting d with d^{IW} and equalizing equilibrium welfares in (29) to (30) yields

$$\frac{5a^2}{9(b + d^{IW})} - 2F = \frac{5a^2}{18b} - F. \tag{a.6}$$

Solving the equation yields the critical value of the differentiation parameter, which is given by

$$d^{IW} = \frac{b\left(5a^2 - 18bF\right)}{5a^2 + 18bF}.$$

The difference between d^{IW} and d^A is given by

$$d^{IW} - d^A = \frac{b\left(5a^2 - 18bF\right)}{5a^2 + 18bF} - \frac{b\left(a^2 - 8bF\right)}{a^2 + 8bF} \tag{a.7a}$$

$$= \frac{44Fa^2b^2}{144F^2b^2 + 58Fa^2b + 5a^4} \tag{a.7b}$$

which is positive. The difference between d^W and d^{IW} is given by

$$d^W - d^{IW} = \frac{b\left(a^2 - 2bF\right)}{a^2 + 2bF} - \frac{b\left(5a^2 - 18bF\right)}{5a^2 + 18bF} \tag{a.8a}$$

$$= \frac{16Fa^2b^2}{36F^2b^2 + 28Fa^2b + 5a^4} \tag{a.8b}$$

which is positive.

A.5 Proof of Lemma 6

To obtain the critical value of the differentiation parameter d^{AW}, substituting d with d^{AW} and equalizing welfares in (45) and (46) yields

$$\frac{3a^2}{4(b + d^{AW})} - 2F = \frac{3a^2}{8b} - F. \tag{a.9}$$

Solving the equation yields the critical value of the differentiation parameter, which is given by

$$d^{AW} = \frac{b\left(3a^2 - 8bF\right)}{3a^2 + 8bF}. \tag{a.10}$$

The difference between d^{AW} and d^{IW} is given by

$$d^{AW} - d^{IW} = \frac{b\left(3a^2 - 8bF\right)}{3a^2 + 8bF} - \frac{b\left(5a^2 - 18bF\right)}{5a^2 + 18bF} \tag{a.11a}$$

$$= \frac{28Fa^2b^2}{144F^2b^2 + 94Fa^2b + 15a^4} \tag{a.11b}$$

which is positive. The difference between d^{W} and d^{AW} is given by

$$d^{W} - d^{AW} = \frac{b\left(a^2 - 2bF\right)}{a^2 + 2bF} - \frac{b\left(3a^2 - 8bF\right)}{3a^2 + 8bF} \tag{a.12a}$$

$$= \frac{4Fa^2b^2}{16F^2b^2 + 14Fa^2b + 3a^4} \tag{a.12b}$$

which is positive.