Competitive Effects of Exchanges or Sales of Airport Landing Slots

by

James D. Reitzes, Brendan McVeigh, Nicholas Powers, Samuel Moy
The Brattle Group

December, 2011

Abstract: We investigate the competitive effects of exchanges or sales of airport landing slots. In our model, airlines with potentially asymmetric slot allocations must decide upon which routes to use their landing slots. When all airlines serve the same routes in a slot-constrained Cournot-Nash equilibrium, small changes in slot allocations among airlines do not affect the overall allocation of slots across routes or air fares. In a symmetric equilibrium where slot-holding airlines have the same number of slots, we find that an increase in the number of slot-holding airlines leads to higher social welfare and consumer surplus, although the number of served routes may decline. Under asymmetric slot allocations, larger slot holders serve "thin" demand routes that are not served by smaller slot holders. In this situation, transfers of slots from larger to smaller slot holders increase social welfare and consumer surplus, even though fewer routes may be served. More generally, our results suggest that increases in slot concentration are harmful to consumers and social welfare, although consumers on relatively thin routes may gain air transportation service as a result.

Competitive Effects of Exchanges or Sales of Airport Landing Slots

James Reitzes

Brendan McVeigh

Nicholas Powers

Samuel Moy*

1. Introduction

Congested airports in the United States (including John F. Kennedy, LaGuardia, Newark Liberty, and Reagan National), Europe (including Heathrow, Paris Orly, and over eighty other airports), and elsewhere (*e.g.*, Brazil, Australia, Japan) explicitly restrict the number of flights that may depart or land from those airports by requiring that airlines have specified time slots for departures and landings. These "landing slot"[1] restrictions effectively place a cap on the total number of flights that may be offered to and from these airports, as well as the number of flights that may be offered by individual airlines which must possess the requisite number of slots. In that sense, they constitute an explicit output restriction on airlines using these slot-constrained airports.

Airlines possessing landing slots have the freedom to choose the routes for which to use their slots. In other words, even though the slot restrictions at John F. Kennedy ("JFK") airport, for example, restrict the total number of flights from the airport, airlines with slots choose the destinations that they fly to (and, correspondingly, the origin points from which they fly directly into JFK). In that sense, an airline's slot holdings impose a constraint similar to that facing a

* The Brattle Group, 1850 M Street, NW; Suite 1200; Washington, DC 20036. Email: james.reitzes@brattle.com or nicholas.powers@brattle.com.

1 The term, "landing slot," is frequently used to refer to slot pairs, which include a landing slot and a take-off slot. Naturally, an airline that wishes to offer a flight between a slot-constrained airport and another city's airport frequently uses both a landing slot and a take-off slot, so that it can both deliver passengers to that city's airport and receive passengers from the same airport.

multi-product firm which must determine how many different products to produce, and how to allocate its output across different products subject to a pre-determined capacity constraint. In this case, the products are different destinations that the airline chooses to serve from the slot-constrained airport, where the overall number of flights that the airline offers to (and from) these destinations does not exceed the number of slots held by the airline. An airline's decision regarding the routes upon which to use its slots is affected by how many other airlines possess slots, the quantity of slots that each possesses, and the routes that each competitor chooses for its slots.

Curiously, the economic literature has not analyzed the competitive impacts that arise from different distributions of landing slots, including how increased concentration in slot holdings affects the number of served routes, consumer surplus, and social welfare. This paper fills that gap by directly addressing these issues, finding that increases in the concentration of slot holdings may frequently reduce both consumer surplus and social welfare even if total output (*i.e.*, the total number of flights) remains the same.

The impact of changes in the distribution of landing slots poses an important policy question, given recent transactions that involve consolidations of slots, such as airline mergers, airline alliance expansion, and outright sales and exchanges of slots. Some recent events that affect slot holdings include the following: (i) the expansion of antitrust immunity granted by the U.S. Department of Transportation (DOT) to the SkyTeam and Star alliances that permitted increased alliance membership (as well as greater profit sharing and coordination over route schedules and pricing); (ii) the grant of antitrust immunity by DOT to the oneworld alliance; (iii) the purchase of landing slots by Continental Airlines at Heathrow airport ($209 million for four pairs of slots)[2]; (iv) the purchase by JetBlue of landing slots at LaGuardia airport (8 pairs for $32 million) and Reagan National airport (8 pairs for $40 million)[3]; (v) the United-Continental merger; and, (vi) the Delta-Northwest merger. Moreover, the European Commission is now in the process of revising its rules regarding the regulation of landing slots, and the Commission is recommending

2 See Financial Times, March 4, 2008, available at http://www.ft.com/intl/cms/s/0/d3c499a8-e98a-11dc-8365-0000779fd2ac.html#axzz1fUr2MOFn.

3 See U.S. Department of Transportation press release (DOT 156-11), "JetBlue, WestJet Gain Slots at LaGuardia, Reagan National Airports," December 1, 2011.

that a secondary market for buying and selling (or exchanging) slots should be developed.[4] The United States and other countries also have debated the best method of allocating and redistributing landing slots in recent years, including the extent to which sales or exchanges of these slots should be allowed.[5]

Not only is the sale or exchange of landing slots an important and timely policy issue, it is also an interesting economic issue, given that total output (*i.e.*, the total number of flights offered from a specified airport) may not be affected by such a transaction but output levels for individual markets (*i.e.*, individual city-pair routes) are likely to be altered. From an economic standpoint, we are effectively analyzing how the behavior of multi-product firms, subject to individual output quotas and a combined constraint on total output, is changed when the output quotas are redistributed across firms, including the possibility that fewer or more firms (*i.e.*, airlines) will be allowed to produce output (*i.e.*, flights). Given that mergers and other forms of horizontal consolidation frequently result in reduced output when synergies are absent, which implies a potential loss of both consumer surplus and social welfare, how different are the effects of consolidation in a multi-product industry when total industry output is fixed?

This is a different economic problem from that encountered in many other industries. The airline slot allocation issue bears some similarity to a situation where there is an import quota and the quota rights can be allocated to different firms in different quantities. However, in that case, the import quota only constrains certain foreign producers as there is typically a domestic industry that produces a substitute product. Also, in cases where quota rights are allocated, firms do not typically face issues regarding the multi-product production of distinct goods (as opposed to different substitutable varieties or qualities of a particular good).[6]

---

4 See European Commission, "Proposal for a Regulation of the European Parliament and of the Council on Common Rules for the Allocation of Slots at European Union Airports," Dec. 1, 2011 (available at http://ec.europa.eu/transport/air/airports/doc/2011-airport-package-slots_en.pdf).

5 See, for example, New York Times, August 11, 2008, available at http://www.nytimes.com/2008/08/12/nyregion/12airport.html; IATA, October 9, 2008, available at http://www.iata.org/pressroom/pr/Pages/2008-10-09-01.aspx; and Washington Post, May 28, 2009, available at http://www.washingtonpost.com/wp-dyn/content/article/2009/05/27/AR20 09052703100.html.

6 While the extraction of resources from a common non-renewable pool is a situation where there is potentially an aggregate output limitation, that limitation is a dynamic one where output can be shifted between periods. By contrast, the limit on landing slots restricts the quantity of output that is produced in any given period. Also, the limit on landing slots is effectively a constraint on the total output produced across multiple markets (*i.e.*, multiple routes).

The prior economic literature on landing slots tends to focus on two distinct issues. First, certain authors (see Borenstein, 1988; Gale, 1994; Starkie, 1998; Brueckner, 2008) focus on the most efficient mechanism for allocating these slots, including whether auctions will produce a socially optimal result. Currently, many slot holders in the United States and Europe have been "grandfathered" their slots based on past operations at particular airports, and then these slots are occasionally traded or sold with government approval. Policymakers have considered alternative allocation or resale mechanisms for these slots. Second, other papers have examined whether there are private incentives to reduce airport congestion absent slots, and how the implementation of congestion taxes or slot restrictions may affect overall congestion levels and correspondingly consumer welfare (see, for example, Mayer and Sinai, 2003; Morrison and Winston, 2007). However, as previously mentioned, there is precious little prior work on how consolidations or divestitures of slot holdings affect airlines' route choices and the number of slots used on a particular route, along with the associated welfare impacts.

We find in general that decreased concentration of slot ownership leads to overall increases in social welfare and consumer surplus that come at the expense of fewer routes being served. Our model assumes that the flights on a given route are homogeneous products (regardless of which airlines offers the flight), and that airlines allocate slots (*i.e.*, flights) across routes consistent with a Cournot-Nash equilibrium, subject to their slot limit. Airlines are identical except for potentially different slot holdings. In a symmetric slot-constrained Cournot-Nash equilibrium, where all slot-holding airlines have the same quantity of slots, we find that an increase in the number of slot-holding airlines may reduce the number of routes served, but it raises both social welfare (*i.e.*, combined producer surplus and consumer surplus) and consumer surplus. This result occurs because, as slot holdings become less concentrated, airlines internalize a progressively smaller portion of the decline in route revenue that results from falling prices when another flight is added to a given route. Consequently, price differences across routes become a more prominent driver of slot allocations as these allocations are spread out across more airlines, leading airlines to move slots from "thin" routes with relatively low margins to "fat" routes with relatively high margins. This not only raises social welfare, it also increases consumer surplus because consumers benefit more from an output increase on these higher margin routes.

A similar effect arises when slots are transferred from an incumbent to an entrant, or from a larger slot holder to a smaller slot holder when the number of slot-holding airlines is held constant. In these cases, such transfers tend to reduce the number of served routes, but increase both social welfare and consumer surplus. Conversely, from the standpoint of competition policy, the results of our model create a rebuttable presumption that increased slot concentration will reduce social welfare and consumer surplus unless there are efficiencies resulting from the slot sale or transfer, such as the movement of slots to a lower cost or otherwise more efficient airline (*e.g.*, including one that will place slots on high-volume routes because of network efficiencies or other economies of density).

However, there is a significant caveat to the above findings. If airlines face large route-level fixed costs, then the above results may be reversed under appropriate conditions. With large route-level fixed costs, when slot holdings become less concentrated, the number of routes served may actually increase and social welfare and consumer surplus may decline. This result arises because additional fixed costs are incurred by an airline when it enters more routes. To avoid incurring these costs, an airline holding a relatively large quantity of slots may decide to place its slots on high-demand routes. If some of those slots are instead given to another airline or an entrant, that airline will incur a route-level fixed cost regardless of what route it decides to enter. Thus, the transfer of slots may result in a movement of slots to a lower-demand route that nonetheless bears a higher price. Since another fixed cost is incurred in the process, social welfare drops and consumer surplus may fall when flights are moved away from high-demand routes.

This paper is organized as follows. Section 2 presents our model, and Section 3 presents our results. Section 4 considers how our results are affected if airlines face route-level fixed costs or handle significant volumes of connecting passengers, as well as providing other caveats and directions for future research. Section 5 offers concluding remarks.

2. <u>The Model</u>

We assume that airlines are identical except for their slot allocations. That is, airlines face the same costs and offer a homogeneous service on a given route. Airlines only offer non-stop point-to-point service; hence, there are no connecting passengers in our model.

The relevant unit of output is a "flight," and one flight requires one slot.[7] For expositional convenience, we assume that flights are uniform in size in that they transport the same number of passengers regardless of the routes that they are used on, and flight costs are identical across routes. Since each flight carries the same number of passengers (and there are no connecting passengers), we can define the market demand function in terms of flights instead of passengers without loss of generality. Also, for expositional simplicity, we normalize the cost of a flight to equal zero.

It can be readily shown that our results are unaffected if we assume alternatively that airlines offer flights of a uniform size on a given route, but that size differs across routes. Also, as long as airlines face the same flight cost on a given route, our results are similarly unaffected if flight costs differ across routes. Also, based on our modeling framework (with costs normalized to zero), when we discuss using landing slots on relatively high-priced routes, it is the same as using those slots on routes with relatively high price-cost margins.

By assumption, there are N airlines, R possible routes, and S total landing slots. Airline i is allocated S_i slots and uses X_{ir} of those slots on route r. The airlines compete in a Cournot game where they simultaneously allocate their slots across some or all of the R routes. Since the number of flights on a route corresponds exactly to the number of slots used on that route, the price of air transportation (*i.e.*, air fare) on route r is effectively determined by the total number of slots used on that route, which we refer to as X_r.

2.1 Demand

We use a general demand construct, represented by the route-level inverse demand function $p_r(X_r)$, where $X_r \geq 0$, that allows for differences in demand across routes. In all cases, it is assumed that the inverse demand function is continuous, twice differentiable, and decreasing. Moreover, we assume that

[7] Technically, there are landing slots and take-off slots. For simplicity, we will assume that "slots" refers to "slot pairs." Thus, one slot consists of a landing and a take-off slot on the same route (*i.e.*, take-off slot from slot-constrained airport A to airport B, and landing from airport B to slot-constrained airport A). Our demand function for a particular route is the demand for tound-trip travel, so that one flight represents one round-trip flight. Also, without loss of generality, we do not distinguish demand by the direction of travel, such that our demand function for a route is effectively consolidated across both directions (*i.e.*, round trip demand from A to B, and round trip demand from B to A).

$$p_r'(X_r) < 0, \text{ and } p_r'(X_r) + p_r''(X_r)X_r < 0, \tag{A1}$$

where the first assumption implies that inverse demand is decreasing in output (*i.e.*, the quantity demanded is decreasing in price), and the second assumption ensures that firm's output choices (*i.e.*, slot quantity choices) are strategic substitutes which is common under Cournot behavior.

2.2 Profit Maximization

Firm *i* (*i.e.*, airline *i*) chooses the quantity of slots to use on a specified route, which is the same as the quantity of flights that it is offering on that route, to maximize its profits subject to the slot allocation decisions made by its rivals. Given that there are *R* possible routes, and that airline *i* has a total allocation of S_i slots, its profit-maximization problem can be stated as follows:

$$\max_{X_{i1},X_{i2},\dots,X_{iR}} \pi\left(X_{i1}, X_{i2}, \dots, X_{iR}\,; X_{j1}, X_{j2}, \dots X_{jR}\,; \forall j \neq i\right) = \sum_{r=1}^{R} p_r\left(X_{ir} + \sum_{j\neq i} X_{jr}\right) X_{ir},$$

$$s.t. \sum_{r=1}^{R} X_{ir} \leq S_{i.} \tag{1}$$

Based on the associated Lagrangean, the first-order conditions are as follows,

$$p_r(X_{ir} + \textstyle\sum_{j\neq i} X_{jr}) + p_r'(X_{ir} + \sum_{j\neq i} X_{jr})X_{ir} - \lambda_i = 0, \quad \text{for all } r \text{ where } X_{ir} > 0,$$

$$p_r(\textstyle\sum_{j\neq i} X_{jr}) \leq \lambda_i \qquad \text{for all } r \text{ where } X_{ir} = 0, \tag{2}$$

where $\lambda_i > 0$ is the shadow value of airline *i*'s slot constraint.

We assume initially that additional slots have positive value for all airlines. This would necessarily be the case if the total slot allocation to all airlines, $S = \sum_{i=i}^{N} S_i$, is less than the number of slots that a monopolist would place on each route. That is,

$S \leq M = \sum_{r=1}^{R} M_r$, where M_r satisfies $p_r(M_r) + p_r'(M_r)M_r = 0$. Otherwise, if $S > M$, there are possible allocations of slots across airlines that might lead to unused slots.

3. Our Results

An important initial finding can be stated as follows:

Proposition 1: If all airlines serve the same routes in a slot-constrained Cournot-Nash equilibrium, and one airline sells or transfers slots to another (or those slots are otherwise reallocated among existing airlines) such that all airlines continue to serve the same routes, then the slot sale or transfer has no effect on either air fares or the total number of flights offered on any given route.

Proof: This is straightforward based on equation (2). If all N airlines serve the same routes in equilibrium, then the first-order conditions for each airline i, as described in equation (2), can be summed to yield the following result for any pair of served routes (s,t):

$$Np_s(X_s) + p_s'(X_s)X_s = Np_t(X_t) + p_t'(X_t)X_t \quad \text{for all } s,t \text{ where } X_s, X_t > 0, \qquad (3)$$

$$\text{s.t.} \sum_{r \in R*} X_r = S, \text{where } R^* = \{r: X_r > 0\}.$$

Note that the solution to equation (3) is independent of the distribution of slots across individual airlines. *QED*

The intuition for the above result is that an airline maximizes its profits by equating marginal revenue (net of flight costs) across all routes that it serves. If all airlines serve the same routes in equilibrium, then the sum of the marginal revenues earned by all airlines is the same across all routes, where this sum equals the route's marginal revenue (*i.e.,* $p_r(X_r) + p_r'(X_r)X_r$) plus a multiple of the route price (*i.e.*, $(N-1)p_r(X_r)$). This leads to a unique allocation of the total number of slots across routes which does not depend on how those slots are allocated among individual airlines.

Note that the above result applies only to allocations where all slots are being used. There may be a slot allocation where one airline receives such a large number of slots that it could not optimally use all of its slots and avoid incurring negative marginal revenues (net of marginal cost). In that case, the airline would choose to leave some of its slots idle if regulatory conditions permitted that behavior. In reality, slot holdings are frequently subject to a "use or lose" constraint.[8] However, if slots could be "parked", then a transfer of some slots from an airline that is "parking" its slots to another airline could lead to increased output and reduced fares even if all airlines continue to serve the same routes.

The key point from Proposition 1, which we will investigate in more detail later, is that slot sales or transfers will not have significant social welfare or consumer surplus impacts unless they occur in situations where airlines serve different routes. However, before we examine the impact of slot transfers or sales under asymmetric slot holdings that cause airlines to serve different routes, we initially examine how welfare is generally affected by increases or decreases in the number of slot-holding airlines, assuming that airlines with slots have identical slot holdings.

3.1 Symmetric Slot Holdings

We now assume temporarily that all airlines with slots hold the same number of slots. First, let us define the conditions that identify a symmetric equilibrium.

Definition: A symmetric slot-constrained Cournot-Nash equilibrium, where N slot-holding airlines have the same number of slots (S/N), satisfies the following conditions:

$$p_s(X_s) + \frac{p_s'(X_s)X_s}{N} = p_t(X_t) + \frac{p_t'(X_t)X_t}{N}$$

$$= \lambda(N,S) \text{ for any pair of routes, } (s,t) \text{, where } X_s, X_t > 0, \qquad \text{(i)}$$

$$\text{s.t.} \sum_{r \in R*} X_r = S, \text{ where } R^* = \{r: X_r > 0\},$$

and

$$p_r(0) \leq \lambda(N,S) \text{ for any } r \text{ where } X_r = 0. \qquad \text{(ii)}$$

---

8 See, for example, Department of Transportation, Federal Aviation Administration, 14 CFR Part 93, "Congestion Management Rule for John F. Kennedy International Airport and Newark Liberty International Airport; Final Rule," Federal Register, Vol. 73, No. 198, October 10, 2008, pp. 60544-71.

Note that, when summed over all N firms, condition (i) is identical to equation (3).

Now, let us place all of the routes in descending order, based on the value of their inverse demand function when output equals zero. Hence, $p_1(0) > p_2(0) > p_3(0) > \cdots > p_R(0)$. Using this ordering, if $R^*(N,S)$ represents the total number of served routes in a symmetric equilibrium, then it must be the case that routes $1, 2, \ldots, R^*(N,S)$ are "served" (*i.e.*, $X_r > 0$ for $r \leq R^*(N,S)$) and all other routes are "not served" (*i.e.*, $X_r = 0$ for $r > R^*(N,S)$).

To see this result, note that it is necessarily suboptimal to serve route s and not serve route t if it holds that $p_t(0) > p_s(0)$. In that case, letting MR_{ir} represent the marginal revenue earned by airline i on route r, it must hold that $p_t(0) > p_s(0) > MR_{is}$. Thus, it is profitable to move some slots from route s to serve route t. Consequently, once routes are placed in descending order of their $p_r(0)$ values, it becomes clear that only the top $R^*(N,S)$ routes are served. For future analysis, we will assume that routes are numbered in descending order of either their "intercept values" (*i.e.*, their $p_r(0)$ values) or their equilibrium prices.[9]

The existence of a symmetric equilibrium is ensured because $Np_r(X_r) + p_r'(X_r)X_r$ is continuous and decreasing in X_r for all r (see assumption (A1)). Hence, with a sufficient number of total slots, there exists a feasible slot allocation that will satisfy equation (3) (and therefore condition (i)) across a given number of routes, R^{**}. By sequentially increasing the number of routes served in the symmetric equilibrium, one may reach a number of routes $R^* < R$ where equation (3) is satisfied and $\lambda(N,S,R^*) > p_{R^*+1}(0)$. In that case, only R^* routes are served in equilibrium. Otherwise, all routes are served in equilibrium.

As stated below, it is important to note that the shadow value of an airline's slot constraint (*i.e.*, $\lambda(N,S)$) increases as a fixed number of slots is divided equally among an increasing number of airlines.

---

9 Our assumptions allow the slope of the demand function to differ across routes. Thus, the route ordering by "intercept values" may differ from the ordering by equilibrium prices, depending on how different the slope of the demand functions are across routes and how slots are allocated across airlines. For example, a route with a lower intercept value (*i.e.*, $p_r(0)$) may have a higher equilibrium price than another route if demand on that route is relatively more elastic.

Lemma 1: Holding the total number of slots S constant, $\boldsymbol{\lambda(N,S)}$ is increasing in N in a symmetric slot-constrained Cournot-Nash equilibrium. Therefore, the number of served routes (i.e., routes where $\boldsymbol{X_r > 0}$) is non-increasing in N. If there exists at least one route r such that $\boldsymbol{\lambda(1,S) < p_r(0) < \lambda(N,S)}$ as $\boldsymbol{N \to \infty}$, then the number of served routes will eventually decrease as N increases. Consequently, decreases in slot concentration tend to reduce the number of served routes.

Proof: See Appendix.

If social welfare and consumer surplus were measured merely by the number of routes served, then one might argue that increasing the concentration of slot holdings was a good thing. However, the increased route coverage comes at a cost of fewer flights and higher fares on "fatter" routes.

The logic behind Lemma 1 is that prices fall as more slots are used on a given route. This price reduction leads to a corresponding reduction in route-level revenue that is more fully internalized in the monopoly case than when the number of airlines increases. Consequently, as a fixed number of slots are divided among more airlines, airlines place relatively greater weight on the absolute price differences across routes when choosing where to use their slots. That is because they internalize a progressively smaller portion of the loss in route revenues associated with the price reductions from adding another flight. Consequently, as *N* increases, an airline uses a higher proportion of its slots on "fat" routes (*i.e.*, routes where $p_r(0)$ is relatively high) and forsakes some of the "thin" routes (*i.e.*, routes where $p_r(0)$ is relatively lower).

Even though the number of served routes may decrease as slots are spread across more airlines, it is actually the case that social welfare and consumer surplus increase with decreased slot concentration, as described in the following proposition.

Proposition 2: In a symmetric slot-constrained Cournot-Nash equilibrium, aggregate social welfare (i.e., combined producer and consumer surplus) and consumer surplus increase as the number of slot-holding airlines increases, despite the fact that the number of served routes may decrease.

Proof: See Appendix

To provide a concrete illustration of the results presented in Lemma 1 and Proposition 2, we construct a simple simulation of a symmetric slot-constrained Cournot-Nash equilibrium. In our example, we hold the total number of slots *S* and the maximum number of routes *R* fixed, and impose some simplifying assumptions on demand, namely that demand across routes is linear and all routes display a common slope coefficient. However, we allow routes to differ in the intercept values of their inverse demand functions; that is, $p_r(0) \neq p_s(0)$ for $r \neq s$.

For illustrative purposes, we consider the case where $S = 200$,[10] $R = 10$, the common slope coefficient is -20, and $\boldsymbol{p_r}(\mathbf{0}) = [2000, 1800, 1650, 1200, 1100, 1000, 750, 720, 550,500]$. Under these conditions, Table 1 displays the differences in equilibrium shadow values, route-level slot usage, consumer surplus, and social welfare in a symmetric Cournot-Nash equilibrium as the number of airlines *N* varies from 1 to 20.

Consistent with our prior results, Table 1 indicates that $\lambda(N,S)$ is increasing in *N*. As a result, the number of routes served in equilibrium is weakly decreasing in *N*. As the shadow value $\lambda(N,S)$ surpasses the intercept value of a given route *r*, that route is no longer served. Thus, decreases in slot concentration tend to reduce the number of routes served. However, consistent with the results in Proposition 2, aggregate social welfare and consumer surplus are both increasing in *N*, as shown in the last two columns of Table 1 (relative to the monopoly case). Thus, our example shows that decreases in route concentration (*i.e.*, increases in the number of airlines with slots) are beneficial to both social welfare and consumer surplus in a symmetric equilibrium, although fewer routes are served.

[10] We assume that slots are divisible: airlines can be allocated a non-integer number of slots, and can allocate their slots across routes in non-integer values.

Table 1: Simulation Results for Symmetric Equilibria with *S* = 200, *R* = 10

This table presents the equilibrium shadow values and total slot allocations for each route in a symmetric slot-constrained Cournot-Nash equilibrium. In this example, there are 10 routes and each has an inverse demand curve with a slope of -20. The number in parentheses below each route r is the intercept of its inverse demand curve, $p_r(0)$. Slot allocations to each airline are symmetric, so dividing the total slot allocation for a route by the number of airlines will yield the airline-level slot allocation. All shadow values and slot allocations are rounded to the nearest 0.1. Estimates of consumer surplus and social welfare (*i.e.*, combined producer and consumer surplus) are shown as percentage increases from the monopoly case.

Airlines (N)	Shadow Value (λ)	Total Slot Allocation										Increase in Consumer Surplus from Monopoly Case	Increase in Social Welfare from Monopoly Case
		Route 1 (2000)	Route 2 (1800)	Route 3 (1650)	Route 4 (1200)	Route 5 (1100)	Route 6 (1000)	Route 7 (750)	Route 8 (720)	Route 9 (550)	Route 10 (500)		
1	327.0	41.8	36.8	33.1	21.8	19.3	16.8	10.6	9.8	5.6	4.3	-	-
2	530.0	49.0	42.3	37.3	22.3	19.0	15.7	7.3	6.3	0.7	0	21%	3.7%
3	610.8	52.1	44.6	39.0	22.1	18.3	14.6	5.2	4.1	0	0	31%	4.6%
4	652.5	53.9	45.9	39.9	21.9	17.9	13.9	3.9	2.7	0	0	36%	5.0%
5	677.5	55.1	46.8	40.5	21.8	17.6	13.4	3.0	1.8	0	0	40%	5.2%
6	694.2	56.0	47.4	41.0	21.7	17.4	13.1	2.4	1.1	0	0	43%	5.4%
8	714.3	57.1	48.3	41.6	21.6	17.1	12.7	1.6	0	0	0	48%	5.5%
10	728.6	57.8	48.7	41.9	21.4	16.9	12.3	1.0	0	0	0	50%	5.6%
12	738.1	58.2	49.0	42.1	21.3	16.7	12.1	0.5	0	0	0	51%	5.6%
20	758.3	59.1	49.6	42.5	21.0	16.3	11.5	0	0	0	0	54%	5.6%

Note that, under our modeling approach, we are able to net welfare losses from reduced flights on certain routes against welfare gains from increased flights on other routes. Aggregate social welfare and consumer surplus effects can be obtained in this fashion, even though it is clearly the case that social welfare and consumer surplus decline on certain routes and increase on other routes.

Social welfare improves because as slot concentration decreases (*i.e.*, the number of airlines holding slots increases), slots are moved from lower-priced routes to higher-priced routes where margins are higher. This necessarily increases market efficiency and raises social welfare. In equilibrium, the higher margin routes are also the routes where changes in output produce a greater impact on consumer surplus (*i.e.*, where $-p_r'X_r$ is higher). Consequently, the movement of slots to higher margin routes also raises consumer surplus.

Lastly, it should be noted here that our welfare results assume that the effects of airport congestion are based on the total number of landing slots in use, not which airlines use those slots and to what destinations they fly. Thus, any consumer surplus and social welfare losses due to airport congestion are not affected by changes in slot allocation patterns, as long as the slots continue to be used.

3.2 Asymmetric Slot Holdings

We now consider how transfers or sales of slots affect consumer surplus and social welfare when airlines have different slot holdings. The following lemma is useful to our analysis.

Lemma 2: Consider an allocation of slots across N airlines described by (S_1,S_2,…,S_N), where $S_1 \geq S_2 \geq \ldots \geq S_N$. In a slot-constrained Cournot-Nash equilibrium, it holds that $\lambda_1 \leq \lambda_2 \leq \ldots \leq \lambda_N$ and that $R_1 \geq R_2 \geq \ldots R_N$, where λ_i represents the shadow value of airline i's slot constraint, and R_i represents the number of routes served by airline i in equilibrium. With routes numbered in descending order of their equilibrium prices, airline i serves only the first R_i routes. Based on the descending order of their $p_r(\mathbf{0})$ values, only the first R_1 routes are served.

Proof: See Appendix.

Based on this Lemma, an airline holding fewer slots than another airline cannot serve more routes than the airline with more slots. This is logical since airlines in our model are identical except for their slot allocations. Given that the slot constraints are binding for each airline, and that marginal revenue is declining in the number of slots that an airline uses on a given route, an airline holding fewer slots realizes higher marginal revenue at its slot constraint than an airline holding more slots. Consequently, an airline with fewer slots has a higher shadow value of its slot constraint, and therefore will not serve any route that would not be served by an airline with more slots. It will serve fewer routes than an airline with more slots if some route has an equilibrium price that lies between its shadow value and the shadow value of the airline with more slots.

The above Lemma is useful for analyzing slot transfers or sales, which produces the following result:

Proposition 3: Let there be a monopoly slot holder that serves more than one route, where price differences exist across routes under monopoly behavior. Any transfer or sale of slots from the monopoly slot holder to an entrant raises social welfare and consumer surplus in a slot-constrained Cournot-Nash equilibrium, even though it may reduce the number of routes that are served.

Proof: See Appendix.

The proof of Proposition 3 also establishes the following result.

Proposition 4: Assume that only two airlines hold slots. Any slot transfer or sale from a larger slot holder to a smaller slot holder (that leaves the smaller slot holder with no more slots than the larger slot holder had prior to the transfer or sale) either raises social welfare and consumer surplus, or it has no effect on social welfare and consumer surplus because route outputs and prices are unaffected. The increase in social welfare and consumer surplus arises in a slot-constrained Cournot-Nash equilibrium even though the number of served routes may decrease.

Proof: See Appendix.

We have seen from Lemma 2 that smaller slot holders use their slots on fewer routes. Since a smaller slot holder has a higher shadow value associated with using a slot, it may not put flights on lower-priced (*i.e.*, "thin") routes where larger slot holders may offer flights. When slots are transferred from a larger slot holder to a smaller slot holder, the smaller slot holder places the additional slots on relatively high-priced (*i.e.*, high-margin) routes, which causes an equilibrium increase in output on higher margin routes and a decrease in output on lower margin routes. These output changes increase both social welfare and consumer surplus, and effectively diminish the degree of price dispersion across routes. The increase in output on "fatter" routes may come at the expense of the larger slot holder abandoning "thinner" routes with relatively low demand (*i.e.*, relatively low $p_r(0)$ values.)

Performing comparative statics on slot transfers becomes more arduous as the number of airlines increases and those airlines serve different numbers of routes. However, it is important to make an assessment regarding whether the above results in Propositions 3 and 4 are likely to hold up as the number of airlines increases. To simplify our analysis, we now assume that there are R^s identical "fat" routes and R^t identical "thin" routes, where the zero output price on the inverse demand curve for fat routes exceeds the corresponding price on the inverse demand curve for thin routes (*i.e.*, $p_s(0) > p_t(0)$). Under these assumptions, we obtain the following result.

Proposition 5: Assume that N airlines hold slots, and there are R^s identical "fat" routes and R^t identical "thin" routes, where $p_s(0) > p_t(0)$. Consider a slot allocation, (S_1,S_2,…,S_N), where $S_1 \geq S_2 \geq \ldots \geq S_N$ and $S_i > S_j$ for some airline pair (i,j). Under these conditions, any slot transfer or sale from a larger slot holder to a smaller slot holder (where that transfer or sale leaves the smaller slot holder with no more slots than the larger slot holder had prior to the transfer or sale) either raises social welfare and consumer surplus, or it has no effect on social welfare and consumer surplus because route outputs and prices are unaffected.

Proof: See Appendix.

Thus, there is a sense that even when there are more than two airlines, slot transfers between airlines which reduce slot concentration also raise consumer surplus and social welfare.

4. <u>Caveats, Extensions, and Directions for Future Research</u>

The above welfare results are obtained in an admittedly somewhat stylized model, where all airlines are identical except possibly for their slot allocations. That is, airlines have identical flight costs on a particular route and produce a homogeneous product. In reality, airlines potentially face different marginal flight costs in serving the same route because of differences in labor costs, fleet composition, fleet vintage, and the airline's overall route configuration as a hub-and-spoke network or point-to-point system. Thus, transfers of slots from smaller slot holders to larger slot holders could still produce beneficial social welfare effects if the larger slot holders are relatively more efficient (*i.e.*, have lower costs) in serving a given route. Consumers may benefit as well if the large slot holder is significantly more efficient in serving higher-volume (*i.e.*, "fat") routes when compared with lower-volume (*i.e.*, thin) routes, so that its slot deployment favors those high-volume routes.

It is also possible that cost savings or other synergies arise directly from an airline (or alliance) possessing a greater number of slots at a particular airport, such as when an airline uses that airport as a hub and is able to achieve scale-related or scope-related operating efficiencies and improvements in service quality as it adds more flights to or from the hub airport.

4.1 Effect on Our Results If Airlines Face Sizeable Route-Level Fixed Costs

To this point, our analysis has assumed that an airline incurs zero fixed costs when entering a new city-pair route. However, it is possible that some costs are incurred if a new route is entered, such as administrative, sales, and marketing costs, as well as costs to obtain facilities including (additional) gates and counter space.

If these route-level fixed costs are small relative to the profit flows from operating flights on a particular route, it is unlikely that our prior results will be altered meaningfully. In order to avoid further price declines on high demand routes where they already operate a significant number of flights, airlines holding large numbers of slots still have incentive to spread their slots across a wider variety of routes than airlines with substantially fewer slots. This incentive will induce large slot-holding airlines to use those slots on lower demand (*i.e.*, lower margin) routes to avoid depressing prices on higher demand routes, sacrificing both social welfare and consumer surplus in the process.

If, however, airlines encounter substantial route-level fixed costs, our results may be substantially different than those described above. Under specialized conditions, it is possible that our previous results are reversed, so that increases in slot concentration lead to fewer served routes, higher social welfare, and higher consumer surplus.

To illustrate this point, which only arises under appropriate conditions, consider the following stylized example. There are 3 routes and 7 total slots. The inverse demand functions for the 3 routes are displayed in Table 2 below. We restrict the slot allocations to each route to be integer-based.

Table 2: Inverse Demand Curves for the Route-Level Fixed Cost Example

This table provides inverse demand curves for each of the three routes in our fixed cost example. For example, if 5 slots (*i.e.*, 5 flights) are allocated to Route 1, the price on the route would be 90. The change in ***total*** route revenue, Δ Rev., from adding a 6[th] slot (*i.e.*, a 6[th] flight) to Route 1is 30, since price on that route would fall by 10 to 80 (hence, Δ Rev. = 80 – 5(10) = 30).

	Route 1		Route 2		Route 3	
P	Q	Δ Rev.	Q	Δ Rev.	Q	Δ Rev.
140	0		0		0	
130	1	130	0		0	
120	2	110	0		0	
110	3	90	0		0	
100	4	70	0		0	
90	5	50	1	90	0	
80	6	30	2	70	0	
70	7	10	3	50	1	70
60	8	-10	4	30	2	50
50	9	-30	5	10	3	30
40	10	-50	6	-10	4	10

Our analysis considers slot allocations to the individual routes in the monopoly case where one airline holds all 7 slots (*i.e.*, $(S_1, S_2) = (7,0)$). This outcome is compared to two different duopoly cases: (i) one airline has 5 slots, and the other airline has 2 slots (*i.e.*, (S_1, S_2) = (5,2)); and, (ii) one airline has 4 slots and the other has 3 slots (*i.e.*, (S_1, S_2) = (4,3)). We then compare slot usage by route, consumer surplus, and social welfare in the monopoly and duopoly cases, assuming that airlines face route-level fixed costs which equal 0, 10, 50, or 150 in our example.

The pure-strategy equilibria results are presented in Table 3, noting however that multiple possible equilibria exist in certain cases. When route-level fixed costs are low or moderate (*i.e.*, when $F = 0$ or 10), we obtain the now familiar result that selling or transferring slots from a monopolist to an entrant results in either fewer served routes or the same number of served routes. Also, social welfare and consumer surplus either improve or remain the same when slot holdings become less concentrated.

However, when route-level fixed costs are high ($F = 150$), selling or transferring slots from a monopolist to an entrant can result in more routes being served—a reversal of the results established thus far in the paper. Moreover, our previous welfare results are also reversed, such that decreases in the concentration of slot holdings may be associated with diminished social welfare and consumer surplus.

With route-level fixed costs, it is difficult to make general inferences about how changes in the concentration of slot holdings affects social welfare and consumer surplus, as the presence of multiple equilibria, including possibly multiple pure-strategy and mixed-strategy equilibria, necessarily complicate any comparative static analysis. Moreover, the equilibrium prices, route-level outputs, and selection of served routes is affected not only by the size of route-level fixed costs, but also by the extent that demand conditions differ across routes and the total number of available slots. Nevertheless, the above example suggests that our prior results are not likely to be significantly altered if the route-level fixed costs facing airlines are relatively small (that is, small relative to the route-level profit opportunity). However, if these costs are sizeable, then it is possible that our prior results will be reversed. That is, as ownership or control of slots becomes less concentrated, more routes may be served and both social welfare and consumer surplus may fall.

Table 3: Equilibrium Strategies and Welfare Results for the Route-Level Fixed Cost Example

This table presents equilibrium slot-usage strategies for each route in an example with three routes and seven total slots, where the inverse demand functions for each route are represented in Table 2 (and where route-level slot usage is restricted to integer values). Airlines face varying route-level fixed costs, and the usage of slots is compared between a monopoly case and two duopoly cases with different airline-level slot allocations. This example demonstrates that the presence of relatively large route-level fixed costs can reverse some of our earlier findings under appropriate conditions. The triples presented below represent route-level slot usage, where the r^{th} number in the triple represents the quantity of slots allocated to route r in a given equilibrium strategy (or strategy pair). As in Table 1, consumer surplus (CS) and social welfare (SW) are presented as percentage increases (or decreases) relative to the monopoly case.

	Monopoly case		Duopoly Case A					Duopoly Case B				
Route fixed costs (F)	Firm 1 ($S_1 = 7$, $S_2 = 0$)	Total	Firm 1 ($S_1 = 5$)	Firm 2 ($S_2 = 2$)	Total	ΔCS	ΔSW	Firm 1 ($S_1 = 4$)	Firm 2 ($S_2 = 3$)	Total	ΔCS	ΔSW
0	(4,2,1)	(4,2,1)	(3,1,1)	(1,1,0)	(4,2,1)	0%	0%	(2,1,1)	(2,1,0)	(4,2,1)	0%	0%
			(3,2,0)	(2,0,0)	(5,2,0)*	38%	3%	(2,2,0)	(3,0,0)	(5,2,0)**	38%	3%
10	(4,2,1)	(4,2,1)	(3,2,0)	(2,0,0)	(5,2,0)	38%	3%	(3,1,0)	(2,1,0)	(5,2,0)	38%	1%
			(4,1,0)	(1,1,0)	(5,2,0)	38%	1%	(2,2,0)	(3,0,0)	(5,2,0)	38%	3%
50	(5,2,0)	(5,2,0)***	(5,0,0)	(0,2,0)	(5,2,0)	0%	0%	(4,0,0)	(0,3,0)	(4,3,0)	-14%	-3%
			(3,2,0)	(2,0,0)	(5,2,0)	0%	-8%	(2,2,0)	(3,0,0)	(5,2,0)	0%	-8%
150	(7,0,0)	(7,0,0)	(5,0,0)	(0,2,0)	(5,2,0)	-41%	-22%	(4,0,0)	(0,3,0)	(4,3,0)	-49%	-26%
								(4,0,0)	(3,0,0)	(7,0,0)	0%	-26%

** Note that there are actually four pure-strategy equilibria when fixed costs are 0 and (S_1,S_2) = (5,2), but in order to simplify the exposition, we have only included in the table those equilibria with the highest and lowest consumer surplus and social welfare. The two equilibria not presented have total slot allocations of (4,2,1) and (5,1,1), and do not change the conclusions of this example.*

*** Similarly, there are four pure-strategy equilibria when fixed costs are 0 and (S_1,S_2) = (4,3), but again, we have only included in the table those equilibria with the highest and lowest consumer surplus and social welfare. The two equilibria not presented have total slot allocations of (4,2,1) and (5,2,0), and do not change the conclusions of this example.*

**** Finally, there is a second possible outcome when fixed costs are 50 and (S_1,S_2) = (7,0), where the equilibrium slot allocation is (4,3,0). When this is the monopoly outcome, transferring slots to an entrant can result in equilibria with higher consumer surplus and social welfare, relative to the monopoly case. This case is consistent with the theoretical results presented earlier. The monopoly outcome represented above was chosen merely to demonstrate the possibility that the presence of large route-level fixed costs could reverse our prior theoretical results under appropriate conditions..*

The intuition for the reversal of our prior welfare results is as follows. When route-level fixed costs are relatively large, an airline with a relatively large number of slots may decide to use more slots on a high demand route even though the marginal revenue (net of marginal costs) from offering an additional flight on that route is less than the marginal revenue from offering an additional flight on a lower demand route. It is worthwhile for the large slot holder to engage in this behavior to avoid incurring the significant route-level fixed costs associated with adding a new route to its network.

If the large slot holder then sells or otherwise transfers slots to an entrant or smaller slot holder, those slots may instead be used on routes that bear a higher price but have relatively modest demand. In this case, the efficiency gain from using slots on a higher price (*i.e.*, higher margin) route may be overcome by the efficiency loss associated with incurring an additional route-level fixed cost, leaving social welfare lower. Consumer surplus also may be lower since prices necessarily increase on the route where there are now fewer flights (*i.e.*, the route where fewer slots are used). If that route is a high demand route, this consumer surplus loss may swamp the gain in consumer surplus arising on the route that receives additional flights (*i.e.*, additional slots) as a result of the slot sale or transfer.

Fixed costs could be significant when an airline adding a route does not already have a presence in the destination airport. However, when the airline already maintains a presence at the destination (*i.e.*, non-slot constrained) airport, route-level fixed costs may be relatively small.

4.2 Impact of Connecting Passengers on Our Analysis

Our previous results derive from a model where there are no connecting passengers. In reality, many airlines carry significant percentages of connecting passengers, particularly those that operate a hub-and-spoke network (as opposed to a point-to-point system). Although connecting passengers are an important part of the air transportation system, we expect that the essence of our above findings will remain intact even when connecting passengers are considered. That is, airlines with large numbers of slots will have a greater incentive to use some of their slots for relatively lower-demand routes, so that they can avoid further depressing air fares on routes where they already offer a significant number of flights. This incentive tends to reduce social welfare and consumer surplus.

Nonetheless, an airline operating a hub-and-spoke network has incentive to use some of its existing slots to fly into its hub airports. This facilitates the transport of the airline's connecting passengers, who typically fly into a hub airport as a means of connecting to their ultimate destination. Profit-maximizing behavior requires that a hub-and-spoke airline equalize the incremental profits from using a slot to add another flight to a hub airport with the incremental profits from using that slot to fly to a non-hub airport, where the marginal profits from carrying a connecting passenger to the hub airport should be the same as those from connecting a non-stop passenger to the hub airport.

If a hub-and-spoke airline operating on a particular route segment is serving both non-stop passengers and a significant percentage of connecting passengers, while a point-to-point airline operating the same number of flights on the same route segment is serving primarily non-stop passengers, then the hub-and-spoke airline would likely earn higher incremental profits (*i.e.*, have a higher slot shadow value) from adding another flight than its point-to-point competitor, unless its costs were substantially higher. This may be the case, for example, if the hub-and-spoke airline uses the slot-constrained airport as a hub. In that case, social welfare and consumer surplus might benefit if relatively more slots are provided to the hubbing airline.

The hubbing airline essentially devotes a smaller percentage of each flight's capacity to non-stop passengers, which may imply that the shadow value of its slot constraint is higher than a non-hubbing competitor with a similar number of slots. Efficiency gains may arise from allowing the hubbing airline to have a relatively large share of landing slots, because it may use those slots on relatively high-priced (*i.e.*, high-margin) non-stop route segments or otherwise use them to transport connecting passengers. This may augment social welfare and consumer surplus, particularly if higher margins are earned on connecting passengers relative to non-stop passengers traveling the same route segments.

At the same time, if these connecting passengers could be readily transported through alternative airports that are not slot-constrained, there is a potentially significant social welfare loss from transporting them through the slot-constrained airport such that they displace non-stop passengers traveling to or from that airport. In essence, some of the shadow cost of the slot constraint is being used to serve passengers who could be served without incurring that shadow cost. Thus, a slot sale or exchange that increases connecting passenger traffic through the slot-constrained airport may reduce social welfare and consumer surplus when there are attractive connecting airports that are not slot constrained.

Another counterbalancing factor that would argue against allowing hub-and-spoke airlines to acquire a disproportionately large share of slots at a slot-constrained airport is if hub-and-spoke airlines were less cost efficient than point-to-point airlines as a result of their network structure. There is some evidence to support that this may be the case, particularly the recent bankruptcies that have affected hub-and-spoke carriers (*e.g.*, American, United, Delta, Northwest, US Airways) in the United States and other industry data suggesting that legacy U.S. hub-and-spoke carriers have higher costs than their newer point-to-point competitors.[11]

5. <u>Concluding Remarks</u>

To limit congestion, certain heavily trafficked airports in the United States, Europe, and elsewhere impose restrictions on the number of landings (and take-offs) at their airports, requiring that airlines possess landing slots. These restrictions effectively limit the total output of an airport, where that output is the number of flights that may land (or take-off) from that airport. However, airlines with landing slots still have considerable freedom in choosing what city-pair routes to serve with their landing slots. With air transportation on each city-pair route potentially representing a distinct product, airlines using a slot-constrained airport effectively must determine which other cities to serve and how many flights to offer on those city-pair routes, subject to a total capacity constraint represented by the number of slots that they hold. Total "industry" output at the slot-constrained airport is similarly restricted to be no greater than the total number of slots that are made available to all airlines serving that airport.

With airlines consolidating through mergers and the expansion of profit-sharing international joint ventures known as alliances (which can receive antitrust immunity), and with airlines directly selling and exchanging airport landing slots, an important policy and economic question has emerged regarding what are the competitive effects of changes in the concentration of slot ownership and control. Curiously, the economic literature has been largely mute on this issue,

---

[11] See, for example, *Reuters* (article by Kyle Peterson and Matt Daily), "American Airlines Files for Bankruptcy," Nov. 29, 2011, available at http://www.reuters.com/article/2011/11/29/us-americanairlines-idUSTRE7AS0T220111129.

letting the question remain unanswered as to whether any general conclusions can be reached regarding the effects of increased slot concentration on prices, route selection, consumer surplus, and social welfare. This paper attempts to remedy that deficiency.

In general, we show that increases in the concentration of slot holdings are harmful to social welfare and consumer surplus, even though total output, represented by the total number of flights across all routes, remains unchanged and the number of served routes may actually increase. In our Cournot-Nash equilibrium model, where airlines choose the routes where they will offer flights and the number of flights to offer on each route (subject to the constraint that the total number of flights they offer must not exceed the number of slots that they hold), an increase in slot concentration across airlines causes fewer slots to be used on higher margin routes and more slots to be used on lower margin routes. As a result, there is an efficiency loss that leads to lower social welfare (*i.e.*, combined consumer and producer surplus). Consumer surplus also falls since the reduction in the number of flights on higher margin routes is associated with losses in consumer surplus that are larger than the gains in consumer surplus that result from an equivalent increase in flights on lower margin routes. We obtain this result regardless whether the increase in slot concentration occurs through a reduction in the number of airlines holding slots, or a sale or exchange of slots that causes a smaller slot holder to lose slots and a larger slot holder to gain slots.

We also have presented an example where, if airlines face significant route-level fixed costs, the theoretical results developed in this paper do not hold. In this case, an airline with a large number of slots may nonetheless concentrate those slots on relatively high demand routes in order to avoid the sizeable fixed costs associated with entering other routes. At the same time, if the large slot holder sells or otherwise transfers slots to an entrant or smaller slot holder, those slots may instead be used on routes that bear a higher price but have relatively modest demand. Under these conditions, the increased efficiency of using slots on a higher priced route may be overcome by the impact of incurring an additional route-level fixed cost, leaving social welfare lower. Consumer surplus also may be lower since prices necessarily increase on the route where there are less flights (*i.e.*, the route where fewer slots are used), and if that route is a high-demand route, the consumer surplus loss swamps the gain in consumer surplus arising on the route that receives additional flights (*i.e.*, additional slots) as a result of the slot sale or transfer.

The potential multiplicity of equilibrium that occur when airlines incur significant route-level fixed costs necessarily make it difficult to perform comparative statics, so that it is difficult to reach general conclusions as to how changes in slot concentration among airlines affect consumer and social welfare in the presence of these costs. However, the presumption seems to be that the results in our paper will continue to hold when these costs are modest relative to route-level profits, but may be overturned in cases where it can be shown empirically that route-level fixed costs are quite sizeable.

Lastly, the presence of connecting passengers also may affect our results. It is possible that an airline that transports a higher share of connecting passengers than another airline with the same number of slots may receive more incremental profits from obtaining an additional landing slot. This is because the airline that transports more connecting passengers is effectively offering less space to non-stop passengers on a particular route segment. This may seem to argue in favor of granting more slots to airlines that carry larger numbers of connecting passengers, particularly if those airlines are likely to use additional slots to fly to their hub airports, and connecting passengers are high-margin passengers relative to non-stop passengers that otherwise might be transported. This argument also depends on an assumption that the airlines transporting large numbers of connecting passengers are not high cost relative to other airlines.

An offsetting argument may arise, however, if the slot-constrained airport itself is being used as a hub for connecting passengers. In that case, there may be a loss in both social welfare and consumer surplus if a slot transfer or sale produces an increase in connecting traffic at the slot-constrained airport, where those connecting passengers could viably be transported through a non-constrained airport.

Appendix

Proof of Lemma 1:

With $\lambda_i(N,S)$ equal to MR_{ir} for each route r that is served under profit-maximizing behavior, one needs to show that $MR_{ir}(N,S)$ is increasing in N with S fixed. Holding the number of served routes $R^*(N,S)$ fixed, this is clearly the case. If the number of slots X_r allocated to any served route r remains unchanged, then $MR_{ir}(N,S) = p_r(X_r) + p_r'(X_r)X_r/N$ is clearly increasing in N. Given this result, for $MR_{ir}(N,S)$ to fall on any served route r (in a symmetric equilibrium), the total number of slots allocated to that route must increase. However, this implies that the number of slots allocated to another route s must decrease, implying that MR_{is} increases on that route (based on the previous result and assumption (A1)). Thus, it is not consistent with profit-maximizing equilibrium behavior for MR_{ir} to decrease. Using similar reasoning, one can show that it is inconsistent with profit-maximizing behavior for an increase in N to lead to an increase in the number of served routes, or a decrease in the number of served routes that produces no increase in marginal revenue for a given airline. Thus, marginal revenue increases with N, which implies that $\lambda(N,S)$ is increasing in N. If there exists at least one route r such that $\lambda(1,S) < p_r(0) < \lambda(N,S)$ as $N \to \infty$, then the number of routes served necessarily decreases as N increases. *QED*

Proof of Proposition 2:

For any two routes, s and t, equilibrium conditions require that $Np_s(X_s) + p_s'(X_s)X_s = Np_t(X_t) + p_t'(X_t)X_t$ (see equation (3)). Totally differentiating this expression, it follows that

$$p_s(X_s)dN + [(N+1)p_s'(X_s) + p_s''(X_s)X_s]dX_s =$$
$$p_t(X_t)dN + [(N+1)p_t'(X_t) + p_t''(X_t)X_t]dX_t,$$

where $(N+1)p_r'(X_r) + p_r''(X_r)X_r < 0$ (see assumption (A1)). When $p_s(X_s) > p_t(X_t)$ and $dN > 0$, this equality cannot be satisfied if $dX_s \leq 0$ and $dX_t \geq 0$. Since $\sum_{r=1}^{R^*(N,S)} dX_r = 0$ (*i.e.*, the total number of slots is fixed), this result implies that there exists route $r^*(N,S)$ such that $dX_r \geq 0$ for $r \leq r^*(N,S)$ and $dX_r < 0$ for $r^*(N,S)+1 \leq r \leq R^*(N,S)$, where routes are numbered in descending order of their equilibrium price. Moreover, $\sum_{r=1}^{r^*(N,S)} dX_r = -\sum_{r=r^*(N,S)+1}^{R^*(N,S)} dX_r > 0$.

Given that flight costs are identical across routes (and normalized to zero), the change in social welfare is $\sum_{r=1}^{R^*(N,S)} p_r dX_r = \sum_{r=1}^{r^*(N,S)} p_r dX_r + \sum_{r=r^*(N,S)+1}^{R^*(N,S)} p_r dX_r$, which is necessarily positive in sign because $\sum_{r=1}^{r^*(N,S)} p_r dX_r > p_{r^*(N,S)}(\sum_{r=1}^{r^*(N,S)} dX_r)$ and $\sum_{r=r^*(N,S)+1}^{R^*(N,S)} p_r dX_r > -p_{r^*(N,S)}(\sum_{r=1}^{r^*(N,S)} dX_r)$. To show that consumer surplus increases, note that the change in consumer surplus on route r equals $-p_r' X_r\, dX_r$. Moreover, if $p_s(X_s) > p_t(X_t)$, then equation (3) implies $-p_s' X_s > -p_t' X_t$. Given this result, and the fact that $dX_r \geq 0$ for $r \leq r^*(N,S)$ and $dX_r < 0$ for $r^*(N,S)+1 < r \leq R^*(N,S)$, it necessarily holds that consumer surplus increases (based on a similar argument to that used for social welfare). *QED*

Proof of Lemma 2:

Consider two airlines, i and j, where $S_i \leq S_j$. With routes numbered in descending order of their equilibrium prices, it is clearly suboptimal to not serve a route that has a higher price than a served route. If both airlines serve the same (number of) routes, then profit-maximizing behavior requires that $X_{ir} \leq X_{jr}$ on any served route. Hence, $MR_{ir} \geq MR_{jr}$ if both airlines serve the same routes.

Also, it is necessarily suboptimal for airline i to serve a route that is not served by airline j. In that case, profit-maximizing behavior by airline i requires that $X_{ir} < X_{jr}$ on any route r served by both airlines, implying that $MR_{ir} > MR_{jr}$. However, on a route s that is served by airline i but not by airline j, it must hold that $MR_{is} < p_s < MR_{jr}$ if airline j is behaving optimally by not entering that route. Thus, $MR_{is} < MR_{ir}$, which is contrary to profit-maximizing behavior by airline i. Therefore, the number of routes served by airline i must be less than or equal to those served by airline j (*i.e.,* $R_i \leq R_j$).

If there is a route s that is served by airline j but not by airline i, it must hold that $MR_{js} < p_s < MR_{ir}$, where r represents any route served by airline i. Consequently, $MR_{ir} \geq MR_{js} = MR_{jr}$, implying that $\lambda_i > \lambda_j$ if $S_i \leq S_j$.

Since airline *1* holds the most slots, it follows that it has the lowest shadow value, λ_1. Profit-maximizing behavior by airline *1* requires that it serve any route r where $p_r(0) > \lambda_1$. Moreover, all other airlines have higher shadow values than airline *1*, implying that no airline serves routes where $p_r(0) \leq \lambda_1$. Therefore, in equilibrium, the first R_1 routes are served, where $p_r(0) > \lambda_1$.

Any other airline i only serves a route r if $p_r\left(\sum_{j \neq i} X_{jr}\right) > \lambda_i$. Thus, if airline i serves R_i routes in equilibrium, profit-maximizing behavior requires that it serves the R_i routes with the highest equilibrium prices (else, there exists a route r not served by airline i where $p_r\left(\sum_{j \neq i} X_{jr}\right) > \lambda_i$). *QED*

Proof of Proposition 3:

Proof: Consider two airlines, i and j, where $S_i < S_j$ and $R_i(S_i,S_j) < R_j(S_i,S_j)$, where R_k denotes the number of routes served by airline k. We can restate the slot allocations as $S_i = \varepsilon$ and $S_j = S - \varepsilon$, so that $R_i = R_i(\varepsilon,S\text{-}\varepsilon)$ and $R_j = R_j(\varepsilon,S\text{-}\varepsilon)$. Clearly, $R_i(0,S) < R_j(0,S)$. If a monopolist serves more than one route (and price differences arise under monopoly), then $R_i(\varepsilon,S\text{-}\varepsilon) < R_j(\varepsilon,S\text{-}\varepsilon)$ for sufficiently small ε. Consistent with Lemma 2, routes are ordered in descending order of their equilibrium price, implying that airline i serves the first R_i routes and airline j serves the first R_j routes.

Now consider a marginal slot transfer from airline j to airline i when $R_i(\varepsilon,S\text{-}\varepsilon) < R_j(\varepsilon,S\text{-}\varepsilon)$. It must hold that $\frac{dX_r}{d\varepsilon} > 0$ for $r \leq R_i$ and $\frac{dX_r}{d\varepsilon} < 0$ for $R_i+1 \leq r \leq R_j$. Suppose not. Since airline j is the only airline using slots on any route r where $R_i+1 \leq r \leq R_j$, and since route marginal revenue is declining in the number of slots used on any given route (by assumption (A1)), profit-maximizing behavior by airline *j* requires that $\frac{dX_r}{d\varepsilon}$ must have the same sign for all *r* such that $R_i+1 \leq r \leq R_j$. Moreover, $\frac{dX_r}{d\varepsilon}$ must have the same sign for all *r* such that $r \leq R_i$. Since both airlines serve any route $r \leq R_i$, it must hold, for any route pair (*s*,*t*) where $s,t \leq R_i$, that $2p_s(X_s) + p_s'(X_s)X_s = 2p_t(X_t) + p_t'(X_t)X_t$ (see equation (3)). Since $2p_r(X_r) + p_r'(X_r)X_r$ is declining in X_r for all routes (see assumption (A1)), $\frac{dX_r}{d\varepsilon}$ must have the same sign for all $r \leq R_i$ in order to conform with equilibrium behavior. Lastly, since there is no change in the total number of available slots, it must hold that $\sum_{r=1}^{R_i} \frac{dX_r}{d\varepsilon} + \sum_{r=R_i+1}^{R_j} \frac{dX_r}{d\varepsilon} = 0$, or $\sum_{r=1}^{R_i} \frac{dX_r}{d\varepsilon} = -\sum_{r=R_i+1}^{R_j} \frac{dX_r}{d\varepsilon}$.

Next, assume that $\frac{dX_r}{d\varepsilon} > 0$ for $R_i+1 \leq r \leq R_j$. If $\frac{dX_r}{d\varepsilon} = \frac{dX_{jr}}{d\varepsilon} > 0$ for $R_i+1 \leq r \leq R_j$, then $\frac{dMR_{jr}}{d\varepsilon} < 0$ for $R_i+1 \leq r \leq R_j$ because route marginal revenue is declining in the quantity of slots used on the route (see assumption (A1)). However, if $\sum_{r=R_i+1}^{R_j} \frac{dX_r}{d\varepsilon} > 0$, then $\sum_{r=1}^{R_i} \frac{dX_r}{d\varepsilon} < 0$, which implies that $\frac{dMR_{jr}}{d\varepsilon} > 0$ for some $r \leq R_i$ and is therefore inconsistent with profit-maximizing behavior.

To see this, note that if $\frac{dX_r}{d\varepsilon} = \frac{dX_{jr}}{d\varepsilon} > 0$ for $R_i+1 \leq r \leq R_j$, there necessarily exists $r \leq R_i$ where $\frac{dX_r}{d\varepsilon} < 0$ and $\frac{dX_{jr}}{d\varepsilon} < 0$. Since $MR_{jr} = p_r(X_r) + p_r'(X_r)X_{jr}$, where $\frac{dMR_{jr}}{dX_r} < 0$ and $\frac{dMR_{jr}}{dX_{jr}} < 0$ (see assumption (A1), it must hold that $\frac{dMR_{jr}}{d\varepsilon} = \frac{dMR_{jr}}{dX_r}\left(\frac{dX_r}{d\varepsilon}\right) + \frac{dMR_{jr}}{dX_{jr}}\left(\frac{dX_{jr}}{d\varepsilon}\right) > 0$ for some $r \leq R_j$. But, this is inconsistent with profit-maximizing behavior by airline *j* because $\frac{dMR_{jr}}{d\varepsilon} < 0$ for $R_i+1 \leq r \leq R_j$. Thus, it cannot hold that $\frac{dX_r}{d\varepsilon} > 0$ for $R_i+1 \leq r \leq R_j$. Similar reasoning shows that it is also inconsistent for slot allocations to remain unchanged on each route. Hence, it must be the case that $\frac{dX_r}{d\varepsilon} < 0$ for $R_i+1 \leq r \leq R_j$, which necessarily implies that $\frac{dX_r}{d\varepsilon} > 0$ for $r \leq R_i$.

Since flight costs are identical across routes (and normalized to zero), the change in social welfare (*SW*) associated with a marginal slot transfer is expressed as follows: $\frac{dSW}{d\varepsilon} = \sum_{r=1}^{R_j} p_r\left(\frac{dX_r}{d\varepsilon}\right) = \sum_{r=1}^{R_i} p_r\left(\frac{dX_r}{d\varepsilon}\right) + \sum_{r=R_i+1}^{R_j} p_r\left(\frac{dX_r}{d\varepsilon}\right) > 0$. This expression is necessarily positive in sign, given that $p_1 > p_2 > \cdots > p_{R_j}$, that $\frac{dX_r}{d\varepsilon} > 0$ for $r \leq R_i$, that $\frac{dX_r}{d\varepsilon} < 0$ for $R_i+1 \leq r \leq R_j$, and that $\sum_{r=1}^{R_i} \frac{dX_r}{d\varepsilon} = -\sum_{r=R_i+1}^{R_j} \frac{dX_r}{d\varepsilon}$.

The change in consumer surplus (*CS*) associated with a marginal slot transfer can be expressed as follows: $\frac{dCS}{d\varepsilon} = \sum_{r=1}^{R_j} -p_r'X_r\left(\frac{dX_r}{d\varepsilon}\right) = \sum_{r=1}^{R_i} -p_r'X_r\left(\frac{dX_r}{d\varepsilon}\right) + \sum_{r=R_i+1}^{R_j} -p_rX_r\left(\frac{dX_r}{d\varepsilon}\right) > 0$. This expression is necessarily positive in sign, given that $-p_1'X_1 > -p_2'X_2 > \cdots > -p_{R_j}'X_{r_j} > 0$, that $\frac{dX_r}{d\varepsilon} > 0$ for $r \leq R_i$, that $\frac{dX_r}{d\varepsilon} < 0$ for $R_i+1 \leq r \leq R_j$, and that $\sum_{r=1}^{R_i} \frac{dX_r}{d\varepsilon} = -\sum_{r=R_i+1}^{R_j} \frac{dX_r}{d\varepsilon}$. To prove that $p_1'X_1 > -p_2'X_2 > \cdots > -p_{R_j}'X_{r_j} > 0$, note that the first-order conditions for firm *j* require that $p_s(X_s) + p_s'(X_s)X_{js} = p_t(X_t) + p_t'(X_t)X_{jt}$ for any pair of routes (*s*,*t*) that it serves. Thus, if $p_s > p_t$, then $-p_s'(X_s)X_{js} > -p_t'(X_t)X_{jt}$. Since an analogous relationship holds for firm *i*, it follows that $-p_1'X_1 > -p_2'X_2 > \cdots > -p_{R_j}'X_{R_j}$.

We now have established that $\frac{dSW(\varepsilon,S-\varepsilon)}{d\varepsilon} > 0$ and $\frac{dCS(\varepsilon,S-\varepsilon)}{d\varepsilon} > 0$ for all ε such that $R_i(\varepsilon,S-\varepsilon) < R_j(\varepsilon,S-\varepsilon)$, which includes $R_i(0,S) < R_j(0,S)$. For all ε such that $R_i(\varepsilon,S-\varepsilon) = R_j(\varepsilon,S-\varepsilon)$ (*i.e.*, airlines i and j serve the same routes), it holds that $\frac{dSW(\varepsilon,S-\varepsilon)}{d\varepsilon} = 0$ and $\frac{dCS(\varepsilon,S-\varepsilon)}{d\varepsilon} = 0$ because a marginal slot transfer has no effect on either air fares or the total number of flights offered on any given route (see Proposition 1). Also, the number of routes served by airline *i(j)* is non-decreasing(non-increasing) in ε. Consequently, for any discrete transfer of ε^* slots from a monopolist to an entrant, where $\varepsilon^* \leq S/2$, the associated changes in social welfare and consumer surplus are, respectively, $\Delta SW(\varepsilon^* \leq S/2) = \int_0^{\varepsilon^*} \frac{dSW(\varepsilon,S-\varepsilon)}{d\varepsilon} d\varepsilon > 0$ and $\Delta CS(\varepsilon^* \leq S/2) = \int_0^{\varepsilon^*} \frac{dCS(\varepsilon,S-\varepsilon)}{d\varepsilon} d\varepsilon > 0$. Given that airlines are identical except for their slot allocations, it holds that $SW(\varepsilon, S-\varepsilon) = SW(S-\varepsilon, \varepsilon)$ and $CS(\varepsilon, S-\varepsilon) = CS(S-\varepsilon, \varepsilon)$. As a result, we have shown that any slot transfer from the monopolist to an entrant raises social welfare and consumer surplus. *QED*

Proof of Proposition 4:

This proof follows directly from the proof of Proposition 3.

Proof of Proposition 5:

First, it can be readily shown that profit-maximizing behavior requires all "fat" routes have the same equilibrium price and output levels, and all "thin" routes have the same equilibrium price and output levels. In equilibrium, either an airline serves both "fat" and "thin" routes, or only those routes with the higher equilibrium price (which are the "fat" routes under appropriate demand conditions). Based on Lemma 2, it must be the case that a smaller slot holder serves no more routes than a larger slot holder.

Consider a marginal slot transfer from a larger slot holder to a smaller slot holder. If both airlines serve the same number of routes, then the slot transfer has no impact on prices, outputs, consumer surplus, or social welfare (by a result analogous to Proposition 1).

If the smaller slot holder serves fewer routes, then profit-maximizing behavior requires that the equilibrium price of routes that it serves is greater than the equilibrium price of routes that it does not serve. Therefore, based on reasoning analogous to that used in the proof of Proposition 3, a marginal slot transfer from a larger slot holder to a smaller slot holder produces a net output increase on the higher priced routes and a net output decrease on the lower priced routes. [If not, and output either increases or stays the same on the lower priced routes, then the summed marginal revenues, $N^* p_r(X_r) + p_r'(X_r) X_{N^*r}$, of the N^* airlines serving the lower-priced routes will decline or remain the same, while their summed marginal revenues necessarily increase on the routes served by all airlines. This is inconsistent with profit-maximizing behavior].

The aggregate increase in output on higher priced (*i.e.*, higher margin) routes, along with an equal aggregate decrease in output on lower priced (*i.e.*, lower margin) routes raises social welfare and consumer surplus, based on reasoning similar to that used in the proof of

Proposition 3. Thus, any marginal slot transfer from a larger slot holder to a smaller slot holder either increases social welfare and consumer surplus, or has no impact on them. Based on this result, it follows that any discrete slot transfer or sale from a larger slot holder to a smaller slot holder (that leaves the smaller slot holder with no more slots than the larger slot holder had prior to the transfer or sale) either raises social welfare and consumer surplus or has no effect.

Since firms are identical in our model except for their slot holdings, it holds that prices, output, social welfare, and consumer surplus are identical in equilibrium if two airlines i and j "reverse" their slot holdings (*i.e.*, $(S_i,S_j) = (S^*,S^{**})$ or (S^{**},S^*)). Thus, any discrete transfer or sale of slots from a larger slot holder to a smaller slot holder, where the smaller slot holder subsequently has more slots than the larger slot holder, but still has fewer slots than the larger slot holder had prior to the transfer or sale, has identical social welfare and consumer surplus effects to another slot transfer or sale which leaves the smaller slot holder with fewer slots than the larger slot holder. *QED*

References

Armantier, Olivier and Oliver Richard. 2008. "Domestic Airline Alliances and Consumer Welfare." *Rand Journal of Economics*, 39(3): 875-904.

Bamberger, Gustavo E., Dennis W. Carlton, and Lynette R. Neumann. 2004. "An Empirical Investigation of the Competitive Effects of Domestic Airline Alliances." *Journal of Law and Economics,* 47, 195-222.

Borenstein, Severin. 1988. "On the Efficiency of Competitive Markets for Operating Licenses." *Quarterly Journal of Economics*, 103(2): 357-385.

_______________. 1989. "Hubs and High Fares: Dominance and Market Power in the U.S. Airline Industry." *Rand Journal of Economics*, 20: 344-365.

_______________. 1990. "Airline Mergers, Airport Dominance, and Market Power." *American Economic Review*, 80: 400-404.

Brueckner, Jan K. 2008. "Slot-Based Approaches to Airport Congestion Management." CESifo Working Paper No. 2302.

_______________ and Pablo T. Spiller. 1991. "Competition and Mergers in Airline Networks." *International Journal of Industrial Organization*, 9: 323-342.

Ciliberto, Federico and Jonathan W. Williams. 2010. "Limited Access to Airport Facilities and Market Power in the Airline Industry." *Journal of Law and Economics*, 53(3): 467-495.

Gale, Ian. 1994. "Competition for Scarce Inputs: The Case of Airport Takeoff and Landing Slots." Federal Reserve Bank of Cleveland Economic Review 30(2): 18-25.

Gayle, Philip G. 2008. "An Empirical Analysis of the Competitive Effects of the Delta/Continental/Northwest Code-Share Alliance." *Journal of Law and Economics*, 51: 743-766.

Kim, E. Han and Vijay Singal. 1993. "Mergers and Market Power: Evidence from the Airline Industry." *American Economic Review*, 83(3): 549-569.

Mayer, Christopher and Todd Sinai. 2003. "Network Effects, Congestion Externalities, and Air Traffic Delays: Or Why Not All Delays Are Evil." *American Economic Review*, 93(4): 1194–1215.

Morrison, Steven A. and Clifford Winston. 2007. "Another Look at Airport Congestion Pricing." *American Economic Review*, 97(5): 1970–1977.

de Oliveira, Alessandro Vinícius Marques. 2010. "Slot Allocation at Congested Airports and its Impacts on Airline Market Power." *Revista de Literatura dos Transportes*, 4(2): 7-49.

Peters, Craig. 2006. "Evaluating the Performance of Merger Simulation: Evidence from the U.S. Airline Industry." *Journal of Law and Economics*, 49, 627-649.

Richard, Oliver. 2003. "Flight Frequency and Mergers in Airline Markets." *International Journal of Industrial Organization*, 21: 907-922.

Starkie, David. 1998. "Allocating Airport Slots: A Role for the Market?" *Journal of Air Transport Management*, 4(2): 111-116.

Werden, Gregory J., Andrew S. Joskow, and Richard L. Johnson. 1991. "The Effects of Mergers on Price and Output: Two Case Studies from the Airline Industry." *Managerial and Decision Economics*, 12: 341-352.