Competitive Effects of Exchanges or Sales of Airport Landing Slots

by

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Abstract: We investigate the competitive effects of exchanges or sales of airport landing slots, using a model where airlines allocate their slot endowments across routes consistent with a Cournot-Nash equilibrium. With symmetric endowments, an increase in the number of slot-holding airlines raises social welfare and consumer surplus. Under asymmetric slot endowments, larger slot holders serve "thin" demand routes that are not served by smaller slot holders. Transfers of slots from larger to smaller slot holders increase social welfare and consumer surplus; however, fewer routes may be served. These results may be reversed if airlines face substantial route-level fixed costs.

Keywords: landing slots, slot exchanges, airline competition, consumer surplus, multi-product production

1. Introduction

Congested airports in the United States (including John F. Kennedy, LaGuardia, Newark Liberty, and Reagan National), Europe (including London Heathrow, Frankfurt, Madrid Barajas, and over 80 other airports), and elsewhere (*e.g.*, Brazil, Australia, Japan) explicitly restrict the number of flights that may depart from or land at those airports by requiring that airlines have specified times—"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 that operate at these airports. In that sense, slot constraints constitute an explicit output restriction on airlines that use these airports.

Airlines that possess landing slots have the freedom to choose the routes where they will use their landing slots. For example, while slot restrictions at John F. Kennedy ("JFK") airport restrict the total number of flights from the airport, airlines that hold slots choose the destinations that they fly to (and from). In that sense, an airline's slot holdings impose a constraint similar to that facing a multi-product firm that must determine 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 could serve from the slot-constrained airport. An airline's slot allocation decision 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.

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. The issue is also an interesting economic question, given that total output (*i.e.*, the total number of flights that are 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. While mergers and other forms of horizontal consolidation in many industries can frequently result in reduced output and losses

[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 (bound for the slot-constrained airport or elsewhere) from the same airport.

in both consumer surplus and social welfare, do the effects of consolidation differ in a multi-product industry when total industry output is fixed? [2]

To the best of our knowledge, there is little prior work on how consolidations or divestitures of slot holdings affect airlines' route choices and the number of slots that are used on a particular route, along with the associated welfare impacts. In this paper, we construct a game-theoretic model to investigate these questions. We find that when route-level fixed costs are low, decreased concentration of slot ownership leads to overall increases in social welfare and consumer surplus, though fewer routes are served. For example, in a symmetric slot-constrained Cournot-Nash equilibrium, 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 and consumer surplus.

A similar effect arises when slots are transferred from a larger slot holder to a smaller slot holder (holding the number of slot-holding airlines constant). Such transfers tend to reduce the number of served routes, but increase both social welfare and consumer surplus. Although these findings arise when airlines face zero or modest levels of route-level fixed costs, we show that they may be reversed if airlines face significant fixed costs in entering individual routes. In that case, more concentrated allocations of slots may actually be associated with fewer routes served and higher social welfare and consumer surplus.

[2] Our slot allocation issue also differs from the usual setting of changes in the concentration of a scarce input, where to the extent that increased concentration harms competition, it does so by reducing output of both the input and the associated downstream industry, which is typically characterized by single-product production. Here, economic interest focuses on the allocation of a fixed input quantity across firms, as well as the resulting firm decisions of how to allocate that input across various products, rather than concentration's impact on the total quantity of input and output that is produced.

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, since there is typically a domestic industry that produces a substitute product. Also, in cases where quota rights are allocated, firms may not face issues with regard to the multi-product production of distinct goods (as opposed to different substitutable varieties or qualities of a particular good).

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. In that setting, an increase in the number of firms can be inefficient as resources are overused from an inter-temporal standpoint.

In the current context of airport slot constraints, there is no inter-temporal substitution. The output limitation is static such that less slot use in one period does not make more slots available in a future period. However, similar to the use of resources from a common pool (such as fish, oil, electromagnetic spectrum, etc.), demand growth over time, coupled with technology improvement, has raised the value of the scarce resource (*i.e.*, slots) and placed more policy focus on how it is allocated.

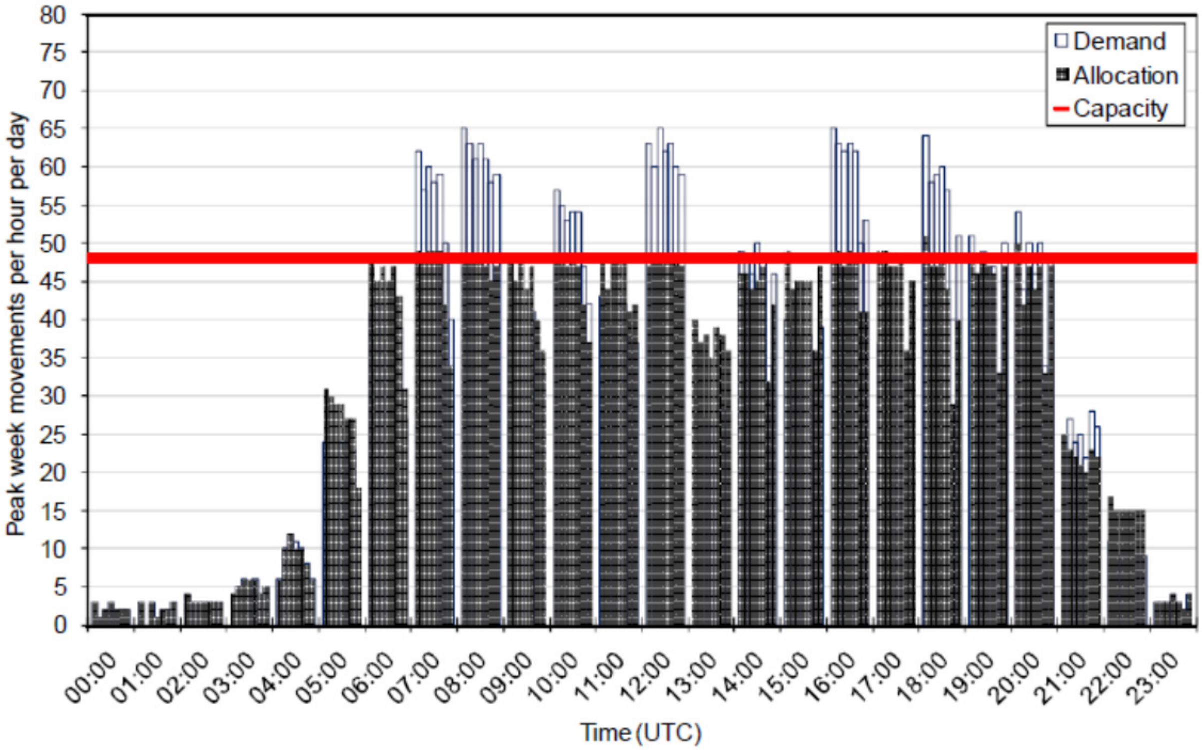
This paper is organized as follows: Section 2 presents some useful institutional background and a brief literature review. Section 3 presents our model, and Section 4 provides our results. Section 5 considers how our results may be affected by heterogeneous costs across airlines, network-related demand effects, connecting passengers, and other factors. Section 6 offers some potentially useful anecdotal evidence with regard to slot allocations (based on the recent slot exchange by US Airways and Delta), and Section 7 has concluding remarks.

2. Institutional Background and Literature Review

Slot holders have the right to schedule a landing or departure during a specific time period. Slot regulations first appeared in the United States in 1969, with the intent of reducing delays at five major metropolitan airports (O'Hare in Chicago, Reagan National in Washington, and LaGuardia, JFK, and Newark in the New York area), under what became known as the High Density Rule. Today, the High Density Rule applies only at Reagan National, though temporary slot controls still apply at all three New York airports.

Slot constraints are also common at airports in the European Union, and affect London Heathrow, Frankfurt, Madrid Barajas, and as many as 86 others. Figure 1, which follows, provides an example of daily slot demand and allocations at Madrid Barajas airport. The capacity constraint binds during much, but not all, of the day.

Figure 1: Arrival Slot Requests and Allocation at Madrid Barajas Airport



Source: European Commission Impact Assessment of revisions to Regulation 95/93, Final Report, March 2011."

Several recent events have affected (or threatened to affect) the concentration of slot holdings at major airports, both in the United States and Europe. These 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, pricing, and use of landing slots); (ii) the grant of antitrust immunity by DOT to the oneworld alliance; (iii) a swap of landing slots at LaGuardia and Reagan National airports by Delta Air Lines and US Airways; (iv) the purchase by Continental Airlines of landing slots at Heathrow airport ($209 million for four pairs of slots);[3] (v) the purchase by JetBlue of landing slots at LaGuardia airport (8 pairs for $32 million) and Reagan National airport (8 pairs for $40 million);[4] and, (vi) the US Airways-American, United-Continental, and Delta-Northwest mergers.[5,6]

3 See *Financial Times* (2008).

4 See U.S. Department of Transportation (2011).

5 Mergers, of course, have competitive effects for reasons other than increased concentration of slot holdings. For example, the U.S. Department of Justice approved the Delta-Northwest merger in part because

The European Commission is now in the process of revising its rules with regard to the regulation of landing slots, and the Commission is recommending that a secondary market for buying and selling (or exchanging) slots should be developed.[7] 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.[8]

The Federal Aviation Administration Modernization and Reform Act of 2012 highlights the importance of air carriers' scheduling practices, including how landing slots are used in determining the price and quality of air transportation service in particular markets. For example, Section 406(b) of that bill mandates that the Department of Transportation review "air carrier flight delays, cancellations, and associated causes," including an assessment of air carriers' scheduling practices.

Despite the increasing policy relevance of issues surrounding the allocation of landing slots, the economic literature has not analyzed the competitive impacts that arise from different distributions of landing slots, including how increased concentration of slot holdings affects the number of served routes, consumer surplus, and social welfare. Instead, the economic literature on slots has focused on other issues.

Certain authors (see Borenstein, 1988; Gale, 1994; Starkie, 1998; Brueckner, 2008) focus on the most efficient mechanism for allocating landing 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.

"[c]onsumers are also likely to benefit from improved service made possible by combining under single ownership the complementary aspects of the airlines' networks" (U.S. Department of Justice, 2008).

6 Slot concentration at two airports was a relevant issue in the recent US Airways – American Airlines merger. The consent decree that allowed the completion of that merger contained a provision that required the merged entity to divest 104 slot pairs at Washington National (DCA) airport and 34 slot pairs at New York LaGuardia airport (LGA). See U.S. Department of Justice (2013). Of the DCA slots, 54 were awarded to Southwest Airlines, 40 to JetBlue, and 8 to Virgin America. At LaGuardia, Southwest won 22 slots while Virgin America won the remaining 12. See Reuters (2014).

7 See European Commission (2011a and 2011b).

8 See, for example, *New York Times* (2008), IATA (2008), and *Washington Post* (2009).

Other authors have examined whether there are private incentives to reduce airport congestion absent slot restrictions, 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).

In addition, Gale and O'Brien (2013) have examined so-called "use-or-lose" provisions, which frequently apply to landing slots. They find that these provisions encourage capacity usage by a dominant firm that might otherwise restrict its own output, but they also encourage the dominant firm to acquire capacity from fringe firms, which has the effect of restricting overall industry output.[9]

3. The Model

We assume that airlines are identical except for their slot allocations; they 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. We discuss the implications of these assumptions later in this paper.

The relevant unit of output is a "flight," and one flight requires one slot.[10] 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. As a further simplification, one could alternatively assume that there is one passenger per flight.

[9] A related body of literature analyzes the implications of other measures that affect airport congestion and concentration. Snider and Williams (2013) find that legislative measures to reduce concentration in airport facilities (*e.g.*, gate availability and other space constrains) were successful in decreasing air fares, with little change in the quality of service. Ciliberto and Williams (2010) find that airport concentration, in the form of control of gates at hub airports, leads to higher fares. Oliveira (2010) finds that increased airport concentration, including slot holdings, facilitated the exercise of market power in Brazil's airline markets. Finally, Forbes (2008) empirically examines the impact of a legislative change in 2000 with respect to take-off and landing restrictions at LaGuardia airport that has the effect of increasing capacity usage, which allows her to estimate the effects of increased air traffic delays on air fares.

[10] 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 slot and a take-off slot on the same route (*i.e.*, take-off slot from slot-constrained airport A to airport B, and landing slot from airport B to slot-constrained airport A). 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).

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.[11] Also, for expositional simplicity, we normalize the cost of a flight to equal zero. Initially, we also assume that route-level fixed costs are zero.

Based on the nature of our proofs, 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. 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, given our modeling framework (where costs are 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.[12]

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-Nash 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.

3.1 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

[11] In our model, airlines choose the number of flights to offer on a particular route (*i.e.*, its route capacity), where each flight requires a slot. Since there are no connecting passengers in our model, choosing the number of flights between A and B is essentially equivalent to choosing the number of non-stop passengers that are transported between A and B, as long as flights operate at full capacity. In the absence of stochastic demand conditions, airlines would seek to fill every seat on their planes in order to maximize revenue, unless filling that seat produces negative marginal revenue, in which case the airline would not have offered the flight. In our model, demand on each route is deterministic.

[12] We assume homogeneous costs across routes merely so that we can refer in the exposition to "high-priced routes" as opposed to "high-priced routes net of flight costs" (*i.e.*, high-margin routes). Allowing airlines on the same route to choose different plane sizes, while facing similar costs in providing a flight for a plane of a specified size, adds additional complexity to our analysis but should not alter the general thrust of our results. Moreover, one would expect that, absent significant heterogeneity in cost efficiency across airlines in using different sizes of planes, airlines would tend to use planes of similar size on the same route as profit-maximizing behavior.

assumed that the inverse demand function is continuous, twice differentiable, and decreasing. Moreover, we assume that

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

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.[13]

3.2 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:

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

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

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

$$\begin{aligned} &p_r(X_{ir} + \textstyle\sum_{j\neq i} X_{jr}) + p_r'(X_{ir} + \textstyle\sum_{j\neq i} X_{jr})X_{ir} - \lambda_i = 0, && \text{for all } r \text{ where } X_{ir} > 0, \\ &p_r(\textstyle\sum_{j\neq i} X_{jr}) \leq \lambda_i && \text{for all } r \text{ where } X_{ir} = 0, \end{aligned} \tag{2}$$

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

[13] The second assumption ensures that an airline's marginal revenue on a specified route is declining in the number of flights that are offered by rival airlines on that route, which is sufficient to ensure that output choices are strategic substitutes.

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 slot allocations across airlines that might lead to unused slots.

4. 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 that are 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):

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

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

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 that 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.[14] 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 affected by increases or decreases in the number of slot-holding airlines, assuming that airlines with slots possess the same quantity of slots.

4.1 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:

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

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

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

and

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

[14] See, for example, Federal Aviation Administration (2008).

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.[15] 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.[16]

The existence of a symmetric equilibrium as defined above 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 that are 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.

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.

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15 We can interpret $p_r(0)$ as either the minimum price on the inverse demand curve that is associated with zero quantity demanded, or the limit of $p_r(X_r)$ as X_r approaches zero.

16 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, $\lambda(N,S)$ is increasing in N in a symmetric slot-constrained Cournot-Nash equilibrium. Therefore, the number of served routes (i.e., routes where $X_r > 0$) is non-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 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. It follows that as *N* increases, an airline uses a higher proportion of its slots on "fat" routes (*i.e.*, routes where $p_r(0)$ is relatively higher) 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: 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 $S = 200$,[17] $R = 10$, 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 shadow values, route-level slot usage, consumer surplus, and social welfare in a symmetric Cournot-Nash equilibrium as the number of slot-holding 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 that are 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 slot 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.

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 clear that social welfare and consumer surplus decline on certain routes and increase on other routes.

[17] We assume that slots are divisible. In other words, airlines can be allocated a non-integer number of slots, and each airline can allocate its 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.

		Total Slot Allocation											
Airlines (N)	Shadow Value (λ)	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)	Increase in Consumer Surplus from Monopoly Case	Increase in Social Welfare from Monopoly Case
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%

Social welfare and market efficiency improve 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. 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.

It should be noted here that our welfare results assume that the level of airport congestion at the slot-constrained airport is based on the total number of landing slots in use, not which airlines use those slots and not which routes the slots are used upon. Thus, any consumer surplus and social welfare losses due to congestion at the slot-constrained airport are not affected by changes in slot allocation patterns, as long as the slots continue to be used.

Lastly, our finding that decreases in market concentration lead to fewer products being offered (*i.e.*, fewer served routes), particularly in the face of capacity constraints, may have implications for markets other than air transportation. Further research is needed to determine how market concentration affects product selection in other retail markets, particularly retail grocery markets where manufacturers of low-volume specialty products complain that they are not able to gain access to the limited available shelf space (without direct payments of "slotting allowances" to the retailer).[18]

4.2 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 that is described by ($S_1,S_2,\ldots,S_N$), 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

[18] Relevant literature related to retail shelf space allocation and slotting allowances includes, among others, Shaffer (1991, 2005), Sullivan (1997), Lanviere and Padmanabhan (1997), and Bloom, Gundlach, and Cannon (2000).

first R_i routes. Based on the descending order of their $p_r(0)$ 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 slot constraints are binding for each airline, and marginal revenue is declining in the number of slots that an airline uses on a given route, an airline that holds fewer slots realizes higher marginal revenue at its slot constraint than an airline that holds 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 that 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. When slots are transferred from an airline that holds a larger quantity of slots to an airline that holds a smaller quantity of slots, 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's abandonment of "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 with regard to whether the above results in Propositions 3 and 4 are likely to hold 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 price that is associated with zero output on the inverse demand curve is higher for fat routes than the corresponding price 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 $\boldsymbol{p_s(0) > p_t(0)}$. Consider a slot allocation, ($S_1, S_2, \ldots, S_N$), 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, even when there are more than two airlines, slot transfers between airlines that reduce slot concentration also tend to raise consumer surplus and social welfare.

4.3 Impact of 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. If, however, airlines encounter substantial route-level fixed costs, the results may be substantially different from those that were 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.

Our analysis considers slot allocations to 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.*, $(S_1, S_2) = (5,2)$), which we refer to as Duopoly Case A; and, (ii) one airline has 4 slots and the other has 3 slots (*i.e.*, $(S_1, S_2) = (4,3)$), which we refer to as Duopoly Case B. 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.

Table 2: Inverse Demand Functions 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 6th slot (*i.e.*, a 6th flight) to Route 1 is 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

For the various assumed levels of route-level fixed costs (hereafter denoted as *F)*, the pure-strategy Cournot Nash equilibria for different slot allocations are presented in Table 3. Referring to this table, we first consider the monopolist's decision (*i.e.*, the "Monopoly Case") when fixed costs equal 0. Facing the marginal revenue schedule described in Table 2, the monopolist will allocate slots to routes such that the marginal revenue is equal (to 70) on all three routes, which leads to an equilbrium slot allocation of (4,2,1) in the absence of route-level fixed costs.

The same equilibrium allocation is obtained when fixed costs are low (*i.e.*, when $F = 10$), since the marginal revenue, net of route-level fixed costs, from adding a single flight on the third route (which, based on Table 2, equals 70 - 10, or 60, when $F = 10$) exceeds the marginal revenue earned from adding an additional flight to either of the first two routes (which equals 50).

However, when $F = 50$, this is no longer true. In particular, the marginal revenue net of F from using the last slot on the third route is now only $70 - 50 = 20$, implying that the monopolist would instead prefer to use its last slot on Route 1 or 2, either of which results in marginal revenue of 50.

Further, when $F = 150$, the additional revenue, net of route-level fixed costs, from serving the second route is less than the additional revenue earned from keeping those slots on the first route instead and avoiding additional fixed costs (see Table 2). Consequently, all slots are used on the first route. The monopoly slot allocations for the different route-level fixed costs described above are presented under the "Monopoly Case" columns in Table 3.

Under duopoly, firms follow analogous decision processes. For a given level of route-based fixed costs, Table 3 shows the possible pure-strategy Cournot-Nash equilibria for each of the two duopoly cases. (It is worth noting that multiple possible equilibria exist under certain conditions.)

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

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 positive 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	Eq'm	Firm 1 ($S_1 = 5$)	Firm 2 ($S_2 = 2$)	Total	ΔCS	ΔSW	Eq'm	Firm 1 ($S_1 = 4$)	Firm 2 ($S_2 = 3$)	Total	ΔCS	ΔSW
0	(4,2,1)	(4,2,1)	a	(3,2,0)	(2,0,0)	(5,2,0)	38%	3%	e	(3,1,0)	(2,1,0)	(5,2,0)	38%	3%
			b	(3,1,1)	(2,0,0)	(5,1,1)	29%	1%	f	(2,2,0)	(3,0,0)	(5,2,0)	38%	3%
			c	(3,1,1)	(1,1,0)	(4,2,1)	0%	0%	g	(2,2,0)	(2,0,1)	(4,2,1)	0%	0%
			d	(2,2,1)	(2,0,0)	(4,2,1)	0%	0%	h	(2,1,1)	(2,1,0)	(4,2,1)	0%	0%
10	(4,2,1)	(4,2,1)	i	(3,2,0)	(2,0,0)	(5,2,0)	38%	3%	k	(3,1,0)	(2,1,0)	(5,2,0)	38%	1%
			j	(4,1,0)	(1,1,0)	(5,2,0)	38%	1%	l	(2,2,0)	(3,0,0)	(5,2,0)	38%	3%
50	(5,2,0)	(5,2,0)*	m	(5,0,0)	(0,2,0)	(5,2,0)	0%	0%	o	(4,0,0)	(0,3,0)	(4,3,0)	-14%	-3%
			n	(3,2,0)	(2,0,0)	(5,2,0)	0%	-8%	p	(2,2,0)	(3,0,0)	(5,2,0)	0%	-8%
150	(7,0,0)	(7,0,0)	q	(5,0,0)	(0,2,0)	(5,2,0)	-41%	-22%	r	(4,0,0)	(0,3,0)	(4,3,0)	-49%	-26%
									s	(4,0,0)	(3,0,0)	(7,0,0)	0%	-26%

Notes: Due to the stylized nature of the demand curves and the restriction to integer allocations, there are multiple pure-strategy equilibria in most of the duopoly cases that are presented above. All pure-strategy Nash equilibria are presented in the table, and are indexed by the letters a-s in order to facilitate discussion.

** 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.*

surplus either improve or remain the same (as compared to the monopoly case) when slot holdings become less concentrated.

Given that multiple pure-strategy equilibria exist, it is useful to consider briefly the issue of equilibrium selection. Consider Duopoly Case A, where one airline has 5 slots and the other airline has 2 slots, under conditions where route-level fixed costs equal 0. Four (simultaneous-move) pure-strategy Cournot-Nash equilibria exist, as is indicated in Table 3. To facilitate our discussion of equilibrium selection, Table 4 depicts the "reduced" normal form of the game, where we present payoffs only for those strategies that survive the process of iterated elimination of strictly dominated strategies.

Suppose, for example, that the route choices are sequential instead of simultaneous. If the larger airline moves first, it will choose the route allocation (3,1,1). Note that the smaller airline is indifferent between playing (2,0,0) and (1,1,0), as shown in Table 4. Consequently, by choosing the route allocation (3,1,1) as its strategy, the larger airline may give itself a positive probability of earning a payoff of 450. By choosing another strategy, the larger airline instead earns a lower payoff of 430. Thus, the likely outcomes if the larger firm moves first are the equilibria labeled b and c in Tables 3 and 4.

By similar reasoning, if the smaller airline moves first instead, it will choose the route allocation (2,0,0). Given that choice by the smaller airline, the larger airline is indifferent between the equilibria labeled a, b, and d in Tables 3 and 4. However, the smaller firm has now given itself a positive probability of earning a higher payoff of 200.

If choices are made simultaneously, the relative likelihood of each of the four pure-strategy equilibria is less clear. However, by choosing the route allocation (3,1,1), the larger airline may give itself a positive probability of the higher payoff associated with equilibrium c. At the same time, by choosing the route allocation (2,0,0), the smaller airline would give itself a positive probability of the higher payoff associated with equilibrium d.

Thus, one might expect that a total route allocation of (5,1,1) could arise with some frequency in Duopoly Case A. When it does, consumer surplus and social welfare are higher

Table 4: "Reduced" Normal Form Game for the Duopoly Case A with *F* = 0

This table presents the reduced normal form game for Duopoly Case A (as labeled in Table 3) when route-specific fixed costs *F* are equal to 0. Only the strategies that have survived the process of iterative elimination of strictly dominated strategies are presented. The first number in each cell represents Firm 1's payoffs while Firm 2's payoffs are listed second. Underlined payoffs indicate that the strategy is a unilateral best response for that firm, while the four bolded payoff pairs denote the four pure-strategy Nash equilibria. The subscripts (a) through (d) index these four equilibria and are consistent with the labeling of equilibrium outcomes in Table 3.

	Firm 2		
Firm 1	(2, 0, 0)	(1, 1, 0)	(1, 0, 1)
(4, 1, 0)	410, 160	440, <u>170</u>	450, 160
(3, 2, 0)	**430, 180**[a]	440, 170	<u>460</u>, 170
(3, 1, 1)	**430, 180**[b]	**450, 180**[c]	450, 160
(2, 2, 1)	**430, 200**[d]	430, 180	440, 170

than the monopoly case.[19]

Moreover, in the situation where route-level fixed costs equal 10, all equilibria under Duopoly Case A (and B) lead to fewer routes being served, but higher consumer surplus and social welfare, when compared to the monopoly case.

As opposed to our prior results, 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, which is a reversal of the results that have been established thus far in the paper. Moreover, as shown in Table 3, 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 affect social welfare and consumer surplus, as the presence of

[19] Similarly, equilibrium selection criteria affect whether the total allocation under Duopoly Case B differs from the monopoly allocation when fixed costs are 0. When the game is played sequentially, the outcome depends in part on the first mover's risk preferences.

When firms move simultaneously, equilibrium selection becomes more challenging. Informally, a risk-dominance criterion might point to equilibrium g in Table 3, which has the same total route allocation as the monopoly case. However, other plausible equilibrium-selection criteria would result in fewer routes being served than the monopoly case. Both outcomes are consistent with our results up to this point: The decrease in concentration that is implied by moving from monopoly to duopoly results in (weakly) fewer routes served and (weakly) increased consumer surplus and social welfare. Payoff matrices of the normal form games for each example are available from the authors upon request.

multiple equilibria, including possibly multiple pure-strategy and mixed-strategy equilibria, necessarily complicate any comparative static analysis. Moreover, equilibrium outcomes also will depend on the total number of available slots and the extent to which demand conditions differ across routes.

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 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. As ownership or control of slots becomes less concentrated, more routes may be served, but both social welfare and consumer surplus may decline.

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 choose to use an additional slot (or 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. By doing this, the large slot holder avoids incurring the significant route-level fixed costs that are associated with adding a new route to its network.

Hence, a large slot holder has a greater incentive to "cluster" its slots in the presence of high route-level fixed costs. If the large slot holder then sells or otherwise transfers slots to an entrant or smaller slot holder, those slots may be used instead on a lower-demand route, where although it has less demand, the use of fewer slots on that route implies it has a higher equilibrium price.

In this case, the efficiency gain from using slots on a higher margin route may be overcome by the efficiency loss associated with incurring an additional route-level fixed cost, thereby reducing social welfare. In essence, excess entry has occurred. Total consumer surplus also may be lower since prices necessarily increase on the higher-demand route where there are now fewer flights.

This result—that large route-level fixed costs provide airlines with more incentive to cluster their flights on high-volume routes—suggests a possible policy implication. The importance of "use-or-lose" provisions that pertain to slots, mentioned earlier, may be increased if there are high route-level fixed costs.

Not only is a large slot holder unwilling to cannibalize profits on existing routes by adding too many flights, it also may be reluctant to enter other routes when route-level fixed costs are high. This provides carriers with additional incentives to "park" their slots, which creates a need for more active oversight and enforcement of "use-or-lose" provisions in the presence of high route-level fixed costs.

However, it also may be economically efficient for airlines to let some of their landing slots remain unused when route-level fixed costs are significant. The cost of entering another route may be higher than the available profits from operating on the route, notwithstanding any market power concerns. Alternatively, the cost of offering an additional flight on a route already served by the airline may be less than the revenue that would be earned from the flight, even if the airline was acting as a price-taker.

Airlines also might argue that slots are property rights that have been given to them as a result of past investments that they have made to support their operations at particular airports or on particular routes. As such, forcing a use-or-lose restriction on slots may be viewed by the airlines as *ex post* opportunism by the policymaker, causing them to make inefficient decisions with respect to route operations and the timing of route investments in order to avoid losing slots.

Thus, a policymaker is potentially faced with the difficult task of distinguishing between slots that are unused as a result of an exercise of market power, as opposed to an economically efficient decision to not utilize the slots.

Route-level fixed costs could be significant when an airline that is adding a route does not already have a presence at 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. Ultimately, further research is warranted as to the magnitude of route-level fixed costs.

5. Caveats and Extensions

For the sake of tractability and to focus on distributional inefficiencies resulting from changes in slot concentration, we have made certain simplifying assumptions. In this section, we discuss the implications for our results if some of those assumptions are relaxed.

5.1 Heterogeneity of Costs and Economies of Density

The above welfare results are obtained in a model where all airlines are identical except possibly for their slot allocations. 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.

Economies of density, which are essentially scale economies that are experienced by an airline at the route-segment level, have been identified in empirical work by Brueckner, Dyer, and Spiller (1992) and others. Their presence suggests that the optimal concentration of slots should balance the cost savings from economies of density with the potential distributional inefficiencies that are highlighted by our model.

However, our model indicates that as the concentration of slots continues to increase, further economies of density will not be realized because an airline increasingly uses incremental slots on either new routes or other routes where it offers a small number of flights. This places a natural limit on slot concentration (as long as economies of density are diminishing, which we would expect).

5.2 Demand Effects and Product Differentiation

Slot concentration also might have implications for demand, if passengers prefer airlines with either a greater menu of destinations or more frequent flights on a given route. The former relies on brand-loyalty effects (or significant consumer value to one-stop shopping) and should not be ignored in any policy formulation, though it is beyond the scope of this paper.

With regard to the latter, it is unclear the extent to which the consumer benefits of greater flight frequency at the route level, such as more convenient departure and arrival times, accrue from a single carrier's schedule or are based on the schedules of all airlines that serve the route. If these benefits are based on the aggregate number of flights on a route (regardless of carrier), increased slot concentration may actually lead to fewer flights on thick routes and further losses of consumer surplus, following the intuition of our model. If they are based on an individual airline's schedule on a particular route, an airline holding several slots would still balance increases in perceived consumer quality from offering more flights on that route against the revenue cannibalization effects that are identified in our model, again resulting in a natural limit to optimal slot concentration.

Product differentiation also may be a relevant consideration, as the "quality" of slots may naturally differ because some departure and landing times are more desirable than others. However, this should not affect our results. Airlines with larger numbers of "high-quality" slots still have incentives to spread them across routes rather than cannibalize their own business and decrease fares for time-sensitive passengers during premium flight times. Similarly, though an airport may not be slot-constrained at all hours of the day, our results would apply in those hours in which it is.

5.3 Contestability

A debated issue in the industrial organization literature with respect to the airline industry is that of contestability, whereby the threat of entry, often by low-cost carriers, disciplines the prices that are charged by incumbent carriers that serve a given route (see, for example, Morrison and Winston, 1987, and more recently Goolsbee and Syverson, 2008, and Kwoka and Shumilkina, 2010). Contestability requires free, instantaneous, and substantial entry, which is certainly not the case if there are route-specific fixed costs.

At the slot-constrained airports that are considered in our model, entry is not free because slots are required. There is a shadow value of using a slot since it can be deployed on alternative routes. Further, only a limited number of airlines hold slots in the first place, so the number of potential entrants on a given route may be quite limited. Airlines also are aware of their ability to drive down air fares by deploying more flights on a given route, which makes them sensitive to the marginal revenue considerations that are described by our model. For these reasons, we do not expect individual routes to behave as contestable markets, particularly when slots are required.

5.4 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 that operates a hub-and-spoke network has an incentive to use some of its existing slots to fly into its hub airports (which may or may not be slot-constrained). 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 that operates on a particular route segment is serving both non-stop passengers and a significant percentage of connecting passengers, while a point-to-point airline that operates 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 would its point-to-point competitor, unless its costs were substantially higher. Since the hubbing airline devotes a smaller percentage of each flight's capacity to non-stop passengers, the shadow value of its slot constraint may be higher than a non-hubbing competitor with a similar number of slots.

Under these circumstances, 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 who travel the same route segments.

The above conclusion would seem valid when a hub-and-spoke airline is not using the slot-constrained airport as its hub, but instead flying connecting passengers between that airport and its hubs. However, if the airline is using the slot-constrained airport as its hub and if connecting passengers could be readily transported through alternative airports that are not slot-constrained, there is a potentially significant social welfare loss from transporting those passengers through the slot-constrained airport such that they displace non-stop passengers traveling to or from that airport.

In this situation, 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, Continental, United, Delta, Northwest, US Airways) in the United States and other industry data that suggest that the legacy U.S. hub-and-spoke carriers have higher costs than do their newer point-to-point competitors.[20]

6. An Anecdotal Empirical Example: US Airways' Slot Acquisition from Delta at Reagan National Airport

While the slot allocation decision is clearly more complex than is depicted in our model here, it is instructive to consider the experience from one recent slot transfer: the recent slot swap whereby US Airways received 42 slot pairs from Delta Air Lines at Reagan National airport (DCA) in Washington, D.C., in exchange for 132 slot pairs at LaGuardia airport in New York. JetBlue also received 8 slot pairs at DCA (from Delta), as part of the terms of approval from government regulators.[21]

In the table below, we compare the average number of non-stop daily departures from DCA to 25 large and mid-size markets that were offered by Delta, US Airways, Jet Blue, and other airlines as of August 2011 and August 2012.[22] For the purpose of this table, "market size" is defined as the overall number of flights from DCA to a given destination; the table has been sorted in descending order of this measure of market size.[23] While airlines' slot allocation decisions have been clearly influenced by certain features of the airline industry that are not included in our model (such as hub importance), the results seem broadly consistent with our model.

For example, as indicated in Table 5, Delta eliminated service from the mid-size markets it was serving as of August 2011 (with the exception of its hubs at Cincinnati, Minneapolis, and Detroit) and concentrated its remaining service on a handful of large markets and hubs. Meanwhile, the largest markets to which US Airways added service were Hartford, Providence, and Minneapolis. In addition, US Airways added service to 14 small markets (not displayed)

[20] See, for example, *Reuters* 2011.

[21] See, for example, *Bloomberg* 2011.

[22] The slot transfer was finalized in December 2011; the decrease in Delta's service and increase in US Airways service was phased in, with the last changes taking effect in mid-July 2012. We have opted to compare August 2011 and August 2012 to minimize the impact of seasonal differences in operations. As far as we are aware, this transfer was the only major change in the slot allocation at DCA during this period.

[23] Large and mid-size markets that are not (and were not) served directly from DCA by any of the carriers involved in the slot swap have been omitted from the table: Chicago, Houston, Cleveland, and Milwaukee.

such as Jacksonville (NC), Bangor (ME), and Augusta (GA); these were markets that were not served by any carrier from DCA as of August 2011. JetBlue (a small slot-holder at DCA) used three of its eight new slots on the DCA-Boston route, which is the largest market that it operated out of DCA.

It is also worth noting that, from August 2011 to August 2012, the net change in the number of average daily departures was negative (or zero) for the 15 largest markets that are identified in Table 5.[24]

[24] Between August 2011 and August 2012, the HHI measuring the concentration of departures by carrier (across all routes) increased from 2752 to 3350, as US Airways' share of departures increased from 44.9% to 54.4%. During the same period, the HHI measuring the concentration of departures by destination (across all carriers) decreased from 279 to 236. In August 2011, there were non-stop flights to 78 different destinations from DCA, with 66 of those routes served by one or more of the three carriers involved in the slot swap. In August 2012, there were 93 destinations that were served non-stop from DCA, with 76 of those routes served by one or more of the three carriers that were involved in the slot swap. These stylized facts (increased concentration of slot operations among carriers leading to decreased concentration among destinations as well as more destinations being served) are broadly consistent with the results of our model.

Table 5: Average Daily Departures from DCA to Selected Cities, Aug. 2011 and Aug. 2012

	Delta flights		US Airways		Jet Blue		All other airlines		Market total
Market	Aug-11	Aug-12	Aug-11	Aug-12	Aug-11	Aug-12	Aug-11	Aug-12	change
New York (EWR)							6	7	
New York (JFK)	5	2					5	5	-4
New York (LGA)	13	11	14	14					
Boston	6	0	13	13	7	10			-3
Atlanta	15	15					6	6	0
Raleigh/Durham			7	7			7	7	0
Dallas / Fort Worth			3	0			12	10	-5
Philadelphia			11	8					-3
Detroit	8	7	4	4					-1
Miami	2	0					9	8	-3
Orlando	3	0	6	6	1	3	1	1	-1
Charlotte			10	10					0
Columbus	3	0	5	5					-3
Nashville			3	3			5	4	-1
Indianapolis	3	0	5	5					-3
Hartford	3	0	4	6					-1
Providence	3	0	4	5					-2
Fort Lauderdale			3	3	1	3	3	2	1
Jacksonville, FL	3	0	4	4					-3
Minneapolis	6	5	0	3					2
Tampa	2	0	4	5	0	1			0
Pittsburgh			5	6					1
St Louis	3	0					3	3	-3
New Orleans	1	0	4	4					-1
Charleston, SC	1	0	4	4					-1
Kansas City			2	3			3	2	0
Cincinnati	4	3	0	3					2

Notes: Table 5 displays the average number of daily non-stop flights (including weekends) from DCA to major markets, as of August 2011 and August 2012. Numbers have been rounded to the nearest integer to simplify exposition. Markets are sorted in descending order by the total number of flights in August 2011. Markets that are not served by the carriers involved in the slot swap have been omitted. Source: OAG data.

7. Conclusion

Certain heavily trafficked airports in the United States, Europe, and elsewhere manage congestion by limiting flight operations through the use of landing slots. Although airlines that hold slots are largely free to choose which routes to serve, these restrictions effectively limit the total output (*i.e.*, total number of flights) of an airport.

Airlines that use a slot-constrained airport must determine which city pairs to serve and how many flights to offer on those city-pair routes, subject to a total capacity constraint that is represented by the number of slots that they hold. As airlines consolidate through mergers and 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 the competitive effects of changes in the concentration of slot ownership and control.

Curiously, the economic literature has been largely mute on this issue. This paper is a first attempt at remedying that deficiency. Under certain conditions, we show that increases in the concentration of slot holdings are harmful to social welfare and consumer surplus, even though total output at an airport remains unchanged and the number of served routes may actually increase. In our Cournot-Nash equilibrium model, 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, which results in losses in consumer surplus and social welfare.

However, if airlines face significant route-level fixed costs, the theoretical results that are developed in this paper may 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 that are 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.

The presence of connecting passengers also could 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 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. However, if the slot-constrained airport itself is being used as a hub, 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 that are allocated to another route s must decrease, which implies 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 that are 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. Given that it has less total slots, 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, $MR_{is} < MR_{jr} < MR_{ir}$ (where r is any route served by both airlines i and j), 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, $MR_{ir} > MR_{js} = MR_{jr}$, 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*

<u>Proof of Proposition 3</u>:

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, which implies 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, let $\frac{dX_r}{d\varepsilon} > 0$ for $R_i+1 \leq r \leq R_j$. This assumption is inconsistent with profit-maximizing behavior by airline 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 $\frac{dX_r}{d\varepsilon} < 0$ and $\frac{dX_{jr}}{d\varepsilon} < 0$ for some $r \leq R_i$. 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 $r \leq R_i$. However, 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 (where it would hold that $\frac{dX_r}{d\varepsilon} = 0$ for $R_i+1 \leq r \leq R_j$). 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) that is 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 $R_i(\varepsilon,S\text{-}\varepsilon) < R_j(\varepsilon,S\text{-}\varepsilon)$, which includes $R_i(0,S) < R_j(0,S)$. For all ε such that $R_i(\varepsilon,S\text{-}\varepsilon) = R_j(\varepsilon,S\text{-}\varepsilon)$ (*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 that are offered on any given route (see Proposition 1). Also, the number of routes that are 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 that 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*

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