Network Effects, Congestion Externalities, and Air Traffic Delays: Or Why All Delays Are Not Evil

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Abstract:

We examine two factors that might explain the extent of air traffic delays in the United States: network benefits due to hubbing and congestion externalities. Airline hubs enable passengers to cross-connect to many destinations, thus creating network benefits that increase in the number of markets served from the hub. Delays are the equilibrium outcome of a hub airline equating high marginal benefits from hubbing with the marginal cost of delays. Congestion externalities are created when airlines do not consider that adding flights may lead to increased delays for other air carriers. Using data on all domestic flights by major US carriers from 1988-2000, we find that excess travel time due to congestion is increasing in hubbing activity at an airport and decreasing in market concentration but the hubbing effect dominates empirically. In addition, hub carriers incur most of the additional travel time due to hubbing, primarily because hub carriers cluster their flights in short spans of time to provide passengers with a large number of potential connections with a minimum of waiting time. Non hub flights at the same hub airports operate with minimal additional travel time. These results suggest that an optimal congestion tax might have a relatively small impact on flight patterns at hub airports since hub carriers already incur a disproportionate share of the hubbing-related congestion.

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1. Introduction

Over the last few years, air traffic delays have garnered increasing attention. The year 2000 produced record delays; more than one-quarter of all flights arrived at least 15 minutes behind schedule. With infrastructure improvements being years away and conventional wisdom holding that delays are caused by congestion externalities, proposed policy remedies have focused on economic solutions such as congestion pricing. However, selecting the appropriate remedy depends crucially on what is causing congestion and delays. In this paper, we try to determine the economic underpinnings of air traffic congestion.

One potential cause of greater travel times is the classic congestion externality, also known as the "tragedy of the commons." According to this hypothesis, congestion occurs because most airports allow unlimited landings and take-offs and airlines add flights without valuing the fact that their traffic will increase travel time for other airlines.[1] Failure to internalize the true marginal cost of adding a flight leads to congestion at airports and flights being delayed. The standard solutions are to use a Pigouvian tax, such as pricing by time of day or the length of a queue, or to restrict traffic and assign property rights by selling ownership of scarce landing slots at congested airports. Previous empirical research has focused on these solutions, suggesting that a congestion tax would have substantial efficiency gains in reducing the level of delays. [Carlin and Park (1970); Morrison and Winston (1989); Daniel (1995); Daniel and Pahwa (2000)]

One problem with the congestion externality explanation for delays, however, is that it is

[1]See models in Vickrey (1969) and Arnott (1979) as examples of transport systems with inefficient congestion.

not consistent with the delay pattern across all US airports. In the "tragedy of the commons," it is usually assumed that there are multiple agents who do not take into account the externality that they create for others. While congestion externalities might not explain why airports without a single dominant carrier, such as La Guardia, Los Angeles, JFK, or Boston, should have high delays, this model may not explain why airports that are dominated by one large carrier, such as Philadelphia, Newark, Atlanta, or Detroit, are consistently among the airports with the largest overall delays.[2]

We propose a second explanation for high air traffic delays: the network benefits associated with the hub and spoke system.[3] Just one new round-trip flight from a hub where an airline already connects to n cities will create $2n$ additional connecting routes. Since the number of potential connections increases exponentially in the number of markets served by the hub carrier, the carrier has an incentive to serve an infinite number of markets. These increasing returns to scale are offset by the limited flight capacities of airports, so a hub airline must trade off the increasing benefits of serving additional markets against rising marginal congestion costs due to higher traffic, such as longer connecting times and greater flight delays. According to this simple model, longer delays at hub airports are the equilibrium outcome of a hub airline equating high marginal benefits from hubbing with the marginal cost of delays.

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[2]Brueckner (2001) shows that a single dominant carrier will internalize much of the externality that would otherwise lead to greater delays. The paper demonstrates that with one or more large carriers at an airport the optimal congestion tax is a decreasing function of the market share of the dominant carrier(s).

[3]See Economides (1996) for a general explanation of the economics of networks and Saloner and Shepard (1995) for an example of empirical evidence in favor of internalized network benefits in the adoption of ATMs.

Below we develop a model that examines the behavior of hub and non-hub airlines operating at a typical airport. Hub airlines want to maximize the number of possible connecting markets for passengers, but also want to minimize passenger travel time spent on congestion delays or waiting for flight connections. The results show that hub carriers often choose to cluster their flights at periodically spaced "hubbing times" to create the greatest variety of passenger destinations, but convenient connections come at the cost of higher congestion. Hub carriers can partially offset the increased congestion by smoothing flight arrival times, albeit by increasing the length of connections for some passengers.[4] Non-hub carriers, who don't obtain network benefits, have no incentive to cluster flights at the same peak hubbing times and thus will incur fewer delays than the hub carrier.[5]

We examine these hypotheses using U.S. Department of Transportation data on flights from 1988-2000 by all major air carriers with more than a one percent US market share, over 66 million flights in total. Our primary measure of congestion delay is the increase in travel time relative to the minimum feasible time on a route. On average, a flight originating at a hub airport requires up to 7.2 minutes longer to travel to its destination than a flight originating at a non-hub airport. Planes flying to a hub airport take up to 4.5 more minutes, on average. Delays at hub airports are increasing in the size of the hub, defined as the number of markets served by the hub

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[4]Smoothing *both* arrivals and departures leads to excessive connection times for some passengers, effectively reducing network benefits. Hub airlines will typically choose to smooth arrivals instead of departures, because of the stochastic nature of flight arrivals.

[5]Daniel (1995), Encaoua *et. al.* (1996), and Borenstein and Netz (1999) come to a different conclusion, suggesting that demand peaks and competition between carriers drives hub and non-hub airlines to cluster their flights at the same departure times. None of these papers incorporates the impact of network effects on scheduling decisions.

carrier. However, the hub carrier itself bears most of the increase in travel time associated with hubs. In all cases, hubbing-related delays are significantly larger for flights departing from a hub than for arriving flights.

The increase in delays associated with hubbing is partially offset by reduced congestion externalities at airports where the hub carrier has a dominant market share. However, the empirical impact of airport concentration (Herfindahl index), which we use as a proxy for the extent to which delay costs are internalized by the carriers at the airport, is much more modest than for hubbing. A 20 percentage point increase in airport concentration leads to a 0.3 to 1.2 minute decrease in travel time for all flights at the airport, depending on whether or not we include airport fixed effects. This effect is similar for both arriving and departing flights.

After 1995, we have more detailed data on travel times and are able to decompose the source of delays. All of the additional travel time due to originating at a hub is spent waiting at the gate or in line on a taxiway waiting to take off. If the destination airport is the airline's hub, some of the excess travel time occurs in the air, but the bulk of the additional delay comes from taxiing to the gate or waiting for a gate to become available. In addition, we can reject the hypothesis that hub carrier delays are the result of cascading delays due to late arriving aircraft on the previous inbound flight.

Alternative views of hub and spoke economics typically emphasize market power or economies of scale rather than the network effects we find. Previous empirical work has shown that hubbing gives the dominant hub carrier significant market power on non-stop flights to and from the hub airport.[6] Some papers attribute the market power associated with hubs to barriers to entry imposed by a dominant airline, such as frequent flyer programs or computer reservation systems. Others argue that airlines benefit from economies of density, so that marginal costs decrease with number of markets served and the scale of service on those routes. [Brueckner *et. al.* (1992), Brueckner and Spiller (1994), Caves *et. al.* (1984)] Hubs may also increase the economic efficiency of an airline's operations. [Hendricks, Piccone, and Tan (1995, 1997); Brueckner and Zhang (2001)] While market power and cost efficiencies are important factors in hub and spoke networks and could explain some delays at hub airports, neither explains why, in the absence of increasing returns to network connections, the hub carrier would accept high delays on its own hub flights relative to non-hub carrier flights to or from the same airport.[7]

The next section discusses the impact of network benefits and congestion externalities on the scheduling decisions of a hub and non hub carrier and the resulting impact on air traffic delays. Section 3 describes the data and discusses our measure of congestion delay. Section 4 presents our empirical specification and results and Section 5 concludes with a policy discussion and an agenda of future research.

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[6]See Borenstein (1990, 1991, 1992, 1993), Borenstein and Rose (1994), Hergott (1997), Kahn (1993), Kim and Singal (1993), Singal (1996), and Zhang (1996) for a discussion of the impact of hubs and having a dominant carrier at an airport on fares.

[7]While large enough declines in average cost with additional markets would generate a positive correlation between markets served and willingness to accept delays, it is inconsistent with hub carriers choosing to concentrate their flights at hubbing times. A carrier that was concerned with gaining low costs associated with serving additional cities, but was not interested in network benefits from connections, would evenly space its flights over the day to reduce congestion costs. Monopoly power raises the benefits of serving all cities, but the marginal benefit of serving any additional city still declines without considering network benefits.

2. Hubbing, Network Benefits, and Flight Delays

In this section, we illustrate how network benefits and congestion externalities lead to greater delays. We also present a series of graphs of scheduled flights at the Dallas-Fort Worth and Boston airports as an example of scheduling practices by hub and non-hub carriers.

Our model generates four basic empirical predictions. First, hub airports should be more congested than non-hub airports since hub airlines receive large network benefits from additional flights and thus are willing to accept greater marginal delay costs. Second, the bulk of the delays at the hub airports should be borne by the hub airlines' flights. Third, hub airlines could have greater delays for departures than arrivals. Finally, an airline's failure to internalize the delays caused to other airline's flights can lead to overscheduling of the airport.

Consumers obtain utility from flights to their preferred destinations, leisure, and a numeraire good, thus the willingness-to-pay for air travel by each consumer is decreasing in the amount of expected travel time. Consumers are be uniformly distributed across all possible origination cities and to have a constant willingness to pay to connect to each potential destination.[8] Aggregating the willingness-to-pay for all consumers yields demand for airline service to a variety of destinations.

We consider two profit-maximizing airlines operating at a single airport. A hub carrier schedules service so that passengers from outlying airports can connect to a variety of destinations and thus obtains increasing returns to scale. If a hub airline already connects to N

[8]Of course, passengers and desired destinations are not uniformly distributed and hub airlines add the highest-demand cities to their networks first. Thus, the increasing returns eventually diminish as the benefit of providing a new destination to the entire network is offset by the fact that few people actually want to fly there. We abstract from this effect since it complicates the model without providing any additional empirical insight.

cities, it serves N^2 markets. Each additional city served increases revenue by 2N. That is, passengers in the new city will have *N* new destinations, while passengers in each of the *N* existing cities will have one more possible destination. An atomistic non-hub airline offers only point-to-point service and thus has constant returns to scale.

The airport operates continuously in discrete periods that we think of as being about 40 minutes long. Connecting passengers must wait at least one period between arriving and departing to allow time to walk from one gate to another. Since passengers prefer shorter connections, airlines receive a discounted fare if passengers take the slower two period connection. We assume passengers are unwilling at any fare to wait more than two periods to connect. Thus passengers arriving in period *t* can connect to any flights departing in periods *t+1* or *t+2*.

Hub airlines choose their number of arrivals (A_t) and departures (D_t) for each period to maximize the following value function, where the first line describes the (net) benefits of operating the flights and second line summarizes the congestion costs.

$$V_h = p\left[\sum_t (A_t + D_t)\right] + q\left[\sum_t f_t A_t D_{t+1} + (1-b)(1-f_t) A_t D_{t+2}\right] \qquad \textbf{(1)}$$

$$-\sum_t \left(A_t + D_t\right)\left(A_t + D_t + N_t\right)$$

The first term in brackets describes the direct net benefits to the hub carrier of operating point-to-point service on a route. That benefit is a linear function of the number of flights operated in each period. The marginal benefit, *p*, incorporates the revenue from fares charged for point-to-point service minus the marginal costs of serving the route segment, including items such as fuel, labor, and the rental costs of aircraft.

The second term in brackets describes the benefits of hubbing and generates increasing returns to scale based on the number of possible connections for each passenger. The additional net revenue obtainable by a hub airline, q, is the price that connecting passengers are willing to pay in excess of the additional resource costs times the number of destinations any passenger can feasibley connect to. On any plane arriving in period t, some fraction of passengers, f_t, connect to a departing plane in the next period and the remainder in the subsequent period. If a hub airline arrives A_t flights in period t, then $f_t \cdot A_t$ passengers can connect to D_{t+1} destinations in the next period and $(1 - f_t) \cdot A_t$ can connect to D_{t+2} destinations in two periods. The discount factor, b, reflects the relative reduction in net revenues associated with two period connections compared to one-period connections. Realistically, b must be between zero and one since when b equals zero, passengers do not require any discount for long connections and when b equals one, tickets for long connections are priced at marginal cost.

The final term in equation (1) describes the congestion costs that carriers face in each period, such as lost revenue from lower fares and higher resource costs. The conversion factor between congestion and revenue is normalized to one. That is, the parameters p and q can be interpreted as the benefit of additional flights and a variety of destinations in congestion cost units. We assume for simplicity that congestion does not spill across periods. In this illustration, congestion increases linearly in the total number of flights in a period, denoted by $A_t + D_t + N_t$, where N_t is the total number of arrivals and departures scheduled by the non-hub carrier in period t.[9] However, the hub carrier only bears the congestion costs incurred by its own flights,

[9]Non-hub aircraft do not need to allow time for passengers to make connections, so we assume that each flight arrives and departs in the same period. This assumption is for notational simplicity and is not critical to our results. All of our findings would hold if we also required the

$(A_t + D_t)*(A_t + D_t + N_t)$.

The hub airline maximizes its value function subject to three equilibrium conditions. First, arrivals and departures in every period must be non-negative. Second, all aircraft that arrive at an airport must eventually leave, so total arrivals must equal total departures. Third, all aircraft must arrive and depart full, so all passengers departing in a period must have connected from arriving flights in the previous two periods and all passengers arriving in a period must connect to departures in the next two periods:

$$D_t = (1 - f_{t-2})A_{t-2} + f_{t-1}A_{t-1} \text{ and } A_t = f_t D_{t+1} + (1 - f_t)D_{t+2} \quad \textbf{(2)}$$

Finally, we must model the flight choices of the non-hub carrier. We make the simplifying assumption that the non-hub carrier operates atomistically, choosing a constant, non-zero number of flights each period.[10] This assumption seems to approximate non-hub airlines' true behavior since non-hub flights are scheduled almost orthogonally to hub carriers'. The correlation between the density of hub and non-hub flights in our sample at hub airports is slightly negative (-0.05) when the hub is operating.[11]

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non-hub carrier to wait one period between arrivals and departures.

[10]Even if we assumed Nash behavior by the non-hub carrier, our empirical predictions would be unchanged, although the solution would become more complicated. All of our key results hold as long as the non-hub carrier does not offset flight reductions by the hub carrier one-for-one. Given the strong network benefits by the hub carrier relative to the non-hub carrier, such one-for-one offsets are extremely unlikely in the context of our model. This view differs from Daniel (1995) who assumes that non-hub and hub carriers receive the same benefits of operating in each period.

[11]While one might expect that non-hub carriers might prefer to operate more flights in less-congested periods, in reality, the non-hub carrier faces a variety of network-related constraints that limit its flexibility in choosing flight times. For example, most non-hub carriers are operating flights to their own hubs, so they might face high costs of moving a flight to a

We maximize equation (1) subject to the constraints in (2). In order to do this, we must make an assumption about how people connect, f_t. If passengers connect uniformly to all possible destinations, one connection mechanism would be that passengers who arrive on a given flight connect based on the share of flights departing in each of the next two periods, or $f_t=D_{t+1}/(D_{t+1}+D_{t+2})$. Another possibility is that passengers who depart on a given flight may have connected based on the share of flights arriving in each of the preceding two periods, or $(1-f_{t-2})=A_{t-2}/(A_{t-2}+A_{t-1})$. Alternatively, both mechanisms may be in effect, with each accounting for half of the connections. Due to the symmetry of the airline's problem, all three connection mechanisms yield the same optimum number of flights. In the first two mechanisms, the distributions of arrivals and departures are reversed. The mixed connection technology finds either distribution of flights to be optimal.

Thus we limit our attention to the case when connections are determined based on the relative shares of the departing flights in the subsequent two periods, $f_t=D_{t+1}/(D_{t+1}+D_{t+2})$. The hub airline's problem is stationary since no passenger remains in the airport for longer than 2 periods. The problem reduces to one of repeated identical banks of three periods each, with any passenger still in the airport at the end of the last period wrapping around to the beginning of the first period of the next bank. Substituting the connection mechanism, f_t, into equations (1) and (2) and imposing that all banks of three periods are identical, the hub airline maximizes:

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different period. Also, the non-hub carrier's aircraft might be forced to incur additional time on the ground to wait for an uncongested period, which would also be costly. Daniel (1995) also fails to reject atomistic behavior by non-hub carriers at Minneapolis airport.

$$V_h = p\left[\sum_{t=0}^{2}(A_t + D_t)\right] + q\left[\sum_{t=0}^{2} A_t \frac{D_{(t+1)\bmod 3}^2}{D_{(t+1)\bmod 3} + D_{(t+2)\bmod 3}} + (1-b)A_t \frac{D_{(t+2)\bmod 3}^2}{D_{(t+1)\bmod 3} + D_{(t+2)\bmod 3}}\right]$$

$$-\sum_{t=0}^{2}\left(A_t + D_t\right)\left(A_t + D_t + N_t\right) \qquad \textbf{(3)}$$

s.t. $D_t = \dfrac{A_{(t-1)\bmod 3} D_t}{D_t + D_{(t+1)\bmod 3}} + \dfrac{A_{(t-2)\bmod 3} D_t}{D_{(t-1)\bmod 3} + D_t}\ \forall t = 0,1,2\,;\quad \sum_{t=0}^{2} A_t = \sum_{t=0}^{2} D_t$

Our first prediction is that hub airports will have more traffic and greater delays than non-hub airports of equivalent size and with equal local demand. This conclusion follows from hub carriers having an increasing marginal benefit from additional flights (q>0) so in equilibrium they are willing to accept a greater congestion cost. In addition, holding the size of the airport constant, the extent of delays increases in the demand for hubbing by the outlying markets. To see these result, maximize equation 3.[12] At the maximum, total hub flights equal:[13]

$$F_h = \sum_{t=0}^{2} A_t^* + D_t^* = 16\frac{p-N}{12 - 8q + 4qb + q^2b^2}$$

[12]This innocuous sentence substitutes for a lot of algebra. Using first order conditions, we maximize equation (3) by imposing all possible permutations of the constraints, one-by-one, and then substituting the solutions for the optimal arrivals and departures back into the value function, choosing the maximum.

[13]Given that b must be between zero and one, an equilibrium exists where the hub operates as long as p is greater than N and q is less than 3/2. Since congestion costs are normalized to one, N is the congestion cost incurred by the first hub flight. If the value of that flight, p, is not greater than the congestion cost, the hub carrier does not operate. The number of flights the hub carrier schedules is multiplied by a function of q, which reflects the increasing returns to scale in hubbing. With a large enough q, the network benefits would grow faster than the congestion costs and the hub carrier would schedule an infinite number of flights, so we assume that case does not hold.

Since the derivative of F_h with respect to p and q is positive, we can draw two conclusions. First, if q were zero, as would be the case for an airline that does not connect passengers, the total number of hub flights would be lower. Second, as demand for air travel increases in the cities surrounding the hub, p and q will rise, leading to a greater equilibrium number of hub flights.[14]

In addition to selecting the total number of flights, the hub airline must also decide how to schedule their flights during the three periods. At the optimum the hub carrier always schedules arrivals in two consecutive periods and clusters all departures in the third period. This outcome occurs because the hub carrier benefits more by ensuring that every arrival can connect to every departure than it loses in increased congestion.

This solution rules out equilibria where not all departures are within two periods of the arrivals. For example, although smoothing arrivals and departures evenly across all three periods minimizes congestion costs, any passenger can connect to at most 2/3 of the destinations. In this case, the loss from the decline in connections is always greater than the savings in congestion. Another alternative would be for the hub carrier to schedule all its arrivals in one period and all the departures in the period immediately after. This approach eliminates costly long connections for passengers but also maximizes congestion. It pays for the airline to smooth some arrivals into the earlier period as long as the reduction in congestion from shifting an arrival one period earlier outweighs the lost revenue from the long connections for some passengers. If the airline smoothed both arrivals and departures, it would create some excessively long 3-period

[14]The derivatives with respect to the other parameters provide intuitive results. The hub carrier schedules more flights when the number of non-hub flights declines (since the average congestion cost is lower); and when b, the cost of long connections, falls (since b lowers the marginal benefit of hubbing).

connections, that have no value to consumers.

The percentage of arrivals scheduled in the first period versus the second depends on the trade-off between the discount associated with two period connections and congestion costs from clustering arrivals in a single period. For reference, assume the airline schedules the arrivals in the periods t and $t+1$ and departures in period $t+2$.[15] Evaluated at the maximum of (3), the share of the total arrivals in period t is $\frac{A_t^*}{A_t^* + A_{t+1}^*} = \frac{1}{2} - \frac{q \cdot b}{4}$. The discount for long connections is expressed in terms of q, the revenue from a connection relative to the congestion cost. When b equals 0, the hub airline faces no discount for long connections and it minimizes connection costs by scheduling half the arrivals in the first period and the other half in the second period. As the unwillingness of passengers to wait for a connection increases, arrivals "tilt" closer to the departures, with fewer arrivals in period one and more arrivals scheduled in the second period. The resulting higher congestion costs are offset by the reduced number of long connections.

Finally, less concentrated airports will have more delays. In our model, hub airlines with low market shares, $\sum(A_t+D_t)/\sum(A_t+D_t+N_t)$, will schedule more flights since less of the increase in average delay due to an additional flight accrues to their aircraft. In other words, an airline imposes a delay externality on other carriers scheduled to fly in the same period. An airline that fully internalized the congestion cost would compute the cost as: $-\sum_{t=0}^{2}\left(A_t + D_t + N_t\right)^2$ rather than the $-\sum_{t=0}^{2}\left(A_t + D_t\right)\left(A_t + D_t + N_t\right)$ cost used in equation 3. The ratio of the actual number of flights relative to the optimal number of flights when the congestion externality is taken into account is $F_h/F_h^*=(p-N)/(p-2N)$. If N is zero, there is no externality and the ratio is equal to one.

[15]Note that for every solution there are three symmetric equilibria, one for each possible "starting" period, but that the choice of starting period is arbitrary given the stationary nature of the problem.

As N increases, the actual number of flights relative to the number that would be scheduled if congestion costs were internalized rises.

All of the model results mentioned above would hold symmetrically with arrivals if we assumed arrival weighting for connections. In that case, the hub carrier would choose to cluster all its arrivals in one period and smooth departures over the subsequent two periods. To choose between the two equilibria, we appeal to the stochastic nature of flight operations, which encourages airlines to smooth arrivals and cluster departures rather than vice versa. Airlines know that some flights will arrive late to the hub, but on a given day do not know which ones will be late. By clustering departures, airlines give themselves the option to depart whichever aircraft arrive first. The data below strongly support the prediction that departure delays at a hub are larger than arrival delays.

Explicitly recognizing that network benefits lead hub carriers to bunch their flights generates empirical predictions that differ from previous research. For example, Daniel (1995) assumes that the hub airline operates at exogenously determined peak times. Around those peak times, the hub carrier clusters its flights to minimize the cost of connections and schedules longer time between arrivals and departures to reduce the likelihood of missed connections. However, non-hub airlines in his model also prefer to fly during the same peaks. Competition to operate in peak periods limits the extent to which hub airlines can smooth the peaks to reduce congestion costs because any reduction of the number of its own flights at the peak will be partly or fully offset by entry of flights by the competitive fringe of non-hub carriers. Daniel concludes that optimal congestion pricing would increase social welfare by encouraging all airlines to smooth their arrival and departure traffic at peak times, reducing congestion.[16] In contrast, by incorporating network benefits our model predicts that only the hub airline gains enough of an economic benefit from clustering its flights to put up with the resulting congestion delays. Thus hub carriers should have substantially higher congestion delays than non-hub carriers operating at the same airport. Since in our model there is less of a congestion externality, the social welfare cost of delays is lower than in Daniel. Also, our model predicts an asymmetry between hub arrival and departure delays, which is not a part of Daniel's framework.

In the model, we assume that airport capacity is fixed over time. However, some airports may have been able to make more efficient use of their runways by adding taxiways. Hub airports, which have peakier demand, might be less willing to invest in additional taxiway capacity than non-hub airports with smoother demand.[17] If the hubbing-driven traffic pattern makes it financially infeasible for hub airports to increase their capacity to accommodate peak congestion, this is an additional mechanism through which hub airports might have higher delays. Nonetheless, differences in capacity expansion between hub and non-hub airports is unlikely to explain the findings that hub airlines incur a disproportionate share of congestion at hub airports, or that there are asymmetries between arrival and departure congestion at hubs.

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[16]Daniel creates an extensive simulation model using data from a week of flights at Minneapolis-St. Paul airport (MSP), combining queuing theory with stochastic, time-varying arrival rates, endogenous scheduling decisions, and a bottleneck model to determine how air carriers should schedule flights within a peak.

[17]Although hub airports face different tradeoffs from spoke airports regarding investments in capacity improvements, these tradeoffs could go in either direction. On one hand, additional capacity at hubs will only be utilized during peak periods rather than throughout the day at a high-demand airport such as La Guardia or Boston. However, the value of the extra capacity might be higher at hubs during the peak periods.

The major predictions of the model are apparent when one looks at the flight schedule from Dallas-Fort Worth (DFW) airport. Figure 1 plots scheduled flights by hub and non-hub carriers at 15 minute intervals from 6 a.m. to midnight for an arbitrary date, Friday October 20, 2000. DFW has two hub carriers, American and Delta, although American operates the bulk of the flights at the airport. DFW is amongst the most congested airports in the country. Two facts are immediately apparent from this figure: 1) flights are clustered into peaks and 2) most of the clustering is due to the hub carriers who bunch their flights together. In addition, Figure 2 shows that the hub carriers at DFW smooth their arrivals much more than departures.

This pattern of clustering flights is not evident at non-hub airports. For comparison, Figure 3 plots total flights at Boston Logan Airport (BOS) on the same date. While Delta and US Airways have fairly large market shares at BOS, neither operates a hub at the airport. Total flights at BOS have many more small ups and downs than at DFW, but DFW flights exhibit much more pronounced peak to trough variability than at BOS.

Clustering by the hub carrier leads to peak flight loads at the airport and delays around hubbing times since non-hub carriers do not fully offset the hub's spikes in flights. Figure 4 plots the total density of flights for hub and non-hub carriers at DFW. While non-hub carriers choose relatively smooth flight levels throughout the day, hub carriers bunch their flights into peaks that are much more pronounced and involve a much larger number of flights. We explore these hypotheses further in the empirical work that follows.

3. Data

In 1988, the US Department of Transportation began requiring all airlines with at least one percent of all domestic traffic to report flight-by-flight statistics on delays for the top 27 airports in the US.[18] This rule was passed as a result of a public outcry over the growth in air traffic delays in the 1980s. In addition, the major carriers covered by this rule agreed to voluntarily report data on all of their flights to or from the remaining domestic airports. Originally, the data included the scheduled arrival and departure time of the flight, the actual arrival and departure time, whether the flight was canceled or diverted, and the flight number. From 1988-1994, airlines excluded information on flights that were delayed or canceled due to mechanical problems. Beginning in 1995, major carriers began reporting information on all scheduled flights, regardless for the reason for a delay or cancellation. In that year, the data was expanded to include the time spent taxiing from the gate to the runway, actual flight time, time spent taxiing to the gate after landing, and the tail number of the aircraft. Our sample includes 66.4 million flights, which is all data over this time period with the exception of flights in 5 months that had substantially missing or corrupted data files.[19]

The most widely reported indicator of congestion is airline on-time performance: the percentage of flights that arrive within 15 minutes of scheduled arrival time. Canceled and diverted flights are treated as late arrivals. One problem with on-time performance as a measure of true delay is that airlines can manipulate it by adjusting their scheduled flight times to compensate for expected delays. However, the total cost to passengers and airlines from congestion or hubbing is a function of how much additional travel time these factors impose.

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[18]A flight is defined as a nonstop segment.

[19] The missing months are July and August 1993, March 1994, May 1999, and December 2000.

Thus we construct a measure of delay that is unaffected by airline scheduling: actual travel time minus minimum feasible travel time. Minimum travel time is defined as the shortest observed travel time on a given nonstop route in a particular month. We consider the minimum feasible time to be a useful benchmark for what travel time would be if airports were sufficiently uncongested and weather were equally favorable. Netting out the minimum time controls for possible changes over time in the types of routes flown or in the performance of the air traffic control system that could affect average flying times. Routes are directional to allow for prevailing winds and other physical differences in travel, so we consider Philadelphia to Los Angeles to be a different route than Los Angeles to Philadelphia. Travel time is computed as the actual arrival time minus the scheduled departure time and thus includes delays in the flight leaving the gate.

Figure 5 plots average minimum travel time, scheduled travel time, and actual travel time. For consistency, the data used in Figure 5 includes only routes where we observe flights in each month of the entire sample period. Actual travel time exceeds minimum travel time by more than 32 minutes in the year 2000. This number has increased more than 10 percent over the sample period, although as we mentioned earlier, changes in reporting between 1994 and 1995 could account for some of that growth. In addition, minimum travel time increased from 89 to 94 minutes over the time period, possibly due to greater traffic system wide.[20] Clearly carriers do

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[20]Since the average route had over 150 flights even in 1988, our lowest-volume year, we believe we measure the minimum time with good accuracy. In principle, however, we are more likely to observe the true minimum travel time on routes with more flights and could overestimate the minimum time on sparse routes. We tried re-estimating our major results with an alternative benchmark, the average travel time for the fastest decile of flights, so as to reduce our reliance on a single flight on a route. The coefficient estimates are slightly smaller this way, although the pattern of delays is the same. The small drop in magnitude of the coefficient

not choose their schedules to have a mean delay of zero. The average delay from schedule of 9.9 minutes is both positive and large and has grown over time. In fact, airlines increased scheduled travel time by only about two-thirds of the growth in average travel time between 1988 and 2000.

We decompose the excess travel time into its component parts in Table 1. Over our sample period, the average flight required about 30.5 minutes more than the minimum feasible travel time on a route. Nearly 10 minutes of that excess is due to a late push-back from the gate. For flights after 1995, about one-half of the total excess travel time on the flight is spent mid-air, though much of that 16 minutes is probably due to less-than-favorable winds and weather en route. Overall, more than one in four flights is canceled or arrives at least 15 minutes late.

Following Section 2, the measure of the size of the hub and thus the extent of network benefits should be the number of possible connections for a traveler through the hub. We define this variable as the number of other airports that an airline flies to from a given airport in a particular month. Airport concentration, which proxies for the extent to which delays are internalized by the carriers, is defined as the Herfindahl index on the share of flights by the various airlines that serve that airport over each one-month period.

The bulk of flights in the US are associated with hubs. Table 1 shows that nearly two-thirds of all flights in the sample originate at an airport that is a hub, with the hub carrier itself originating a little more than one-half of hub flights (39 percent of total flights). In all, 83 percent of flights either originate or land at some carrier's hub and almost three-quarters of all flights occur on an airline flying to or from its own hub. With the strong prevalence of hubbing,

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estimates (approximately 10 percent) is likely due to the fact that even flights in the fastest decile of the distribution may be impacted by congestion at hubs.

the typical airport has a HHI of 0.40, although there is substantial variation across airports.

Table 2a identifies the hub carriers and reports airport concentration for all airports with at least one percent of the total flights in November 2000. Cincinnati, dominated by a Delta hub, was the most concentrated large airport that month at 0.91. Charlotte and Pittsburgh, both US Airways hubs, were close behind at 0.81. Not every airport with a hub carrier is highly concentrated. Many single-hub airports are only moderately concentrated, such as Newark (0.38 with a large Continental hub) and Salt Lake City (0.48 with a large Delta hub). Hubs with less connection activity, such as United in San Francisco, have much lower concentrations (0.33). Some airports have multiple hub airlines, such as Chicago's O'Hare with United and American and only 0.38 concentration. Also, some busy airports do not have hubs with significant connecting activity: Chicago Midway with a concentration of 0.71 or New York's La Guardia which has a concentration of 0.22.

Overall, there has been substantial consolidation since 1988, especially in the early 1990s, when mergers and bankruptcies reduced the number of major carriers in the sample from 14 to 10.[21] The remaining airlines have continued to expand their hub and spoke systems, although a few carriers abandoned previous hubs. As a result, many airports looked quite different in 1988 than they do in the year 2000. Table 2b presents the same snapshot of all airports with at least one percent of the total flights in November 1988. For example, relative to 1988, Denver and Atlanta each lost one of their hub carriers. Miami, Washington National, and Cleveland gained a single hub carrier, Las Vegas and Los Angeles gained two hub carriers, and Phoenix added a

[21]See Morrison (1996) for a discussion of the policy issues relating to the merger trend in the airline industry.

second hub carrier. JFK, Orlando and, Raleigh Durham lost their hubs altogether. Several cities had a change of hub airline or a change in the size of the hub. Finally, airport concentration has varied over this time period, with many airports exhibiting a general increase in concentration, a few airports exhibiting a strong rise in concentration as a single carrier consolidated its hubbing at that airport, and several airports showing a decline in concentration as hub carriers pulled out. In many regression specifications below, we will use this variation in hub size and concentration within an airport over time to identify their effects on delays.

4. Estimation and Results

We examine the empirical predictions from Section 2 regarding the impact of network benefits and congestion externalities on delays. First, flights operating at hub airports should face delays that increase with the size of the hub. Second, most delays at hub airports should be incurred by the hub airline itself since the bulk of its flights are during congested peaks, and these delays should also be increasing in the size of the hub. Third, delays should be longer for flights that originate at a hub than flights arriving at a hub, as hub airlines cluster their departures more than their arrivals. Finally, congestion externalities should cause higher delays at less concentrated airports, holding the extent of hubbing constant.

To examine these predictions, we estimate the following base empirical specification:

$$\begin{aligned}
\text{DELAY}_{ijkmt} &= \alpha + \beta_1 \text{ CONCENTRATION}_{org,kt} + \beta_2 \text{ CONCENTRATION}_{dest,mt} + \\
&\theta_1 (\text{HUB AIRPORT}_{org})_{kt} + \theta_2 (\text{HUB AIRPORT}_{dest})_{mt} + \\
&\gamma_1 (\text{HUB AIRLINE x HUB AIRPORT}_{org})_{jkt} + \gamma_2 (\text{HUB AIRLINE x HUB AIRPORT}_{dest})_{jmt} + \\
&+ \Psi_1 (\text{DEMAND}_{org})_{mt} + \Psi_2 (\text{DEMAND}_{dest})_{mt} + \delta_1 \text{ YEAR}_t + \delta_2 \text{ MONTH}_t \\
&+ \delta_3 \text{ AIRLINE}_j + \delta_4 \text{ AIRPORT}_{org,k} + \delta_5 \text{ AIRPORT}_{dest,m} + \varepsilon_{ijkmt}
\end{aligned}$$

where DELAY is a measure of travel time or on-time performance of flight *i* on airline *j* from airport *k* to airport *m* on date *t*. CONCENTRATION refers to the airport concentration of the origin (*k*) or destination (*m*) airport. HUB is measured both at the airport level (whether airport *k* is a hub for any airline) and the airline level (whether airline *j* has a hub at airport *k*). An airline's hub is defined as a function of the number of airports airline *j* flies to from airport *k*. We generate dummy variables for three different ranges of the number of destination airports: 26 to 45, 46 to 70, and 71 or more.[22] Concentration and hub are included separately for both the origin and destination airports to allow for separate effects for each end of the flight.

We also include DEMAND variables to control for changes in local demand for air travel over time and across Metropolitan Statistical Areas (MSAs) that might lead to greater flight delays. All equations include annual population, employment, and per-capita income. For airports in a MSA, we include their MSA values, but also interact the economic variables with a dummy variable that equals one if the airport is the largest airport in the MSA, a proxy for the likeliest airport to be a hub. For airports not in a MSA, we interact a non-MSA dummy or Alaska airport dummy with national values of the economic variables.[23] Most of these economic variables are of the expected sign and are statistically significant.

All specifications have dummies for the year and month of travel to control for unobserved time and seasonal factors that may affect system wide delays, and for the airline, *j*, to

[22]Our results are robust to alternative functional form assumptions, but we find that the categories provide a better fit than a linear function and are more easily interpretable than a higher-order polynomial.

[23]Almost all airports in our data set that are not in an MSA and not in Alaska are located at destination vacation spots. Many are airports at ski resort locations.

control for unobserved airline quality. Finally, most specifications are run with a full set of fixed effects for the airport the flight originates from (k) and the airport it arrives at (m) to control for unobserved airport heterogeneity that may affect delays, such as capacity.

Given that we have data on more than 66 million flights, we take two steps to make estimation more manageable. First, we narrow our data to all flights on Fridays.[24] Second, in our base specification we generate cells of flights by each airline on every route for all months in every year, a total of more than 617,150 airline-route-month/year cells. Within each cell we compute the mean of the dependent variable and all independent variables, and use these cell means in the regressions that are reported in this paper. These regressions are weighted by the number of flights within the cell. These weighted least squares coefficient estimates are identical to what we would obtain using OLS, since none of the independent variables in our basic specification vary within the cells. We compute robust standard errors, allowing the residuals to be correlated over time within a route.

Airport level findings:

Below, we find large and significant effects of hubbing and moderate effects of concentration on delays. Our initial evidence is presented in Table 3. The dependent variable is excess travel time above the minimum feasible travel time. Consistent with our characterization of network benefits from hubbing, hub airports have more delays. In column 1, flights originating and arriving at hub airports face delays of up to 7.2 and 4.5 minutes, respectively. In addition, hub delays increase monotonically in the size of the hub. Flights that originate from the

[24]We construct the independent variables in our regressions using all data, not just Fridays. In addition, we have conducted some preliminary estimation on Saturdays, the least busy day of the week, and obtain the same basic results.

smallest hubs are delayed four minutes more than flights departing from non-hub airports, 6.7 minutes at medium size hubs, and 7.2 at the largest ones. A similar pattern holds for flights flying to hub airports, although the coefficients are uniformly smaller in magnitude.

We also find evidence that airports with low concentration have higher delays, possibly because carriers do not fully internalize the costs their flights impose on other carriers. In column (1), higher concentration has a small but beneficial impact on delays. Controlling for the extent of hubbing, a one standard deviation increase in concentration (0.20) leads to a modest 1.2 minute decline in delay at both origin and destination airports. Even an increase from the mean concentration level of 0.40 to an airport with just one airline leads to just a 3.6 minute decrease in delays, smaller than the effect of hubbing.

One potential problem with this regression is the possibility that our income, employment, and population variables might not fully control for local demand. In particular, airports with high unobserved local demand for air travel might have a greater number of flights and also have a hub that serves a large number of destinations. Thus high levels of congestion may be due to local demand rather than hubbing. To address this issue, we take two approaches.

In column (2), we instrument for the probability that an airport is a hub with variables that are based on the demand for connections by surrounding communities, rather than by the hub city. We compute the distance from a given airport to all of the other airports in our sample, counting the number of airports within 500 miles, 500-1000 miles, and 1000-1500 miles, and also sum up the population and per-capita income for the airports within each of those rings. This gives the total demand for connections around each airport, both in terms of number of connecting airports and economic buying power of the potential connections. The demand variables are also interacted with a dummy variable that indicates the primary airport within each MSA. Such an interaction is important to differentiate the largest airport from smaller secondary airports within an MSA. These instruments are significant in the first stage and are moderately successful in isolating the hub delay effect from local demand. For origin airports, the hub variables are still individually and jointly significant and nearly as large as the OLS coefficients, suggesting that hubs are associated with greater congestion. However, the destination hub variables are much smaller than the OLS coefficients and are not statistically significant. While the instruments can successfully identify hubs, separate origin and destination effects may be harder to pin down. Overall, the estimation is consistent with greater origination delays at hub airports.

In the third column we include airport fixed effects. By effectively looking only at changes over time within airports in hubbing, concentration, and delays, we absorb time-invariant airport level factors such as capacity or local demand. However, by including fixed effects, we eliminate a large source of variation–differences in hubbing and delays across airports. The fixed effects estimates present the same pattern as the earlier estimation, except the coefficients are considerably smaller. The biggest hubs have the largest delays and delays increase with the size of the hub. The coefficient on the smallest category of origin and destination hubs is negative, suggesting that these hubs appear to have slightly better performance than non hub airports. However, the negative coefficients themselves are small. Concentration also reduces delays, although the coefficients are much smaller than in the estimates that do not include fixed effects. To the extent that cross sectional variation is required to identify airport level hubbing and concentration effects, the fixed effects estimates might provide a lower bound on the true effects.

Within-airport clustering of flights:

In Table 3 (part II) column (4), we move on to consider an important implication of our model of network benefits: that the hub carrier should have greater delays than non-hub carriers at hub airports. In this case we include separate covariates for flights by the hub carrier to or from its own hub airport. With airport fixed effects, the hub/non-hub carrier effect is identified based on differences between hub and non-hub airlines within each airport, so all carriers at the airport are subject to identical capacity constraints and face the same level of local demand. The results suggest that the dominant hub carrier incurs most delays at hub airports. Relative to non-hub airlines at the same airport, hub airlines have excess travel time of up to 5.5 minutes at origin airports and 2.8 minutes at destination airports. Estimated delays accruing to the hub airline increase monotonically in the size of the hub and are larger for origin airports. All of these results are consistent with the existence of strong network benefits that lead to more delays for hub airlines. This result also supports the view that the peaks of traffic occur at hubbing times rather than merely popular times to fly. If the latter were the case, then non-hub carriers would have just as strong a desire to fly during the most congested peaks and their flights would be delayed just as much as the hub carriers. To the degree that delays between the two types of airlines differ, it is evidence for hub aircraft having greater value of flying in the peaks due to the network benefits.[25]

In this regression, airport-level hub variables indicate the extent of delays by non-hub

[25]While hub and non-hub flight densities are virtually uncorrelated, the share of hub flights scheduled at congested peaks is quite high and non-hub flights are scheduled diffusely throughout the day. Hence the result that delays accrue mainly to hub carriers.

airlines at a hub airport. In column (4), the coefficients on the airport level variables become much smaller in magnitude, and are sometimes even negative. The negative coefficient indicates that the non-hub airlines have slightly lower delays when they operate at smaller hubs rather than at non-hub airports, possibly benefitting from scheduling some of their flights at times when there are few hub airline flights. Even with these changes, the results suggest that the performance of non-hub carriers deteriorates monotonically with hub size and that non-hub carriers at the largest hubs face worse delays than carriers that operate at airports without a hub. Airport concentration remains negative and statistically significant, but its estimated magnitude in the fixed effects specifications is small when compared to the hub variables. A large increase in the HHI from 0.40 to 1.0 leads to a 1.1 to 1.6 minute decrease in delays, less than one-third of the increase in travel time associated with the largest hub airlines.

While hub carriers need to cluster their departures to maximize network connection benefits, Section 2 shows that they can smooth their arrivals somewhat as long as the cost of long connections is not too high. If delays come from peak loads of traffic at hubs, arrivals should exhibit lower hub-induced delays than the more clustered departures. Our results support this conclusion since the effect of hubbing on originating flights is much larger than on arriving flights in every specification. The delays due to concentration do not depend on clustering of flights and thus should not exhibit a systematic pattern of being larger for origin or destination airports. Indeed, the estimated concentration effects are similar for both types of airports.

Finally, we consider one other factor potentially affecting our results. During the sample period, all airlines were free to choose their preferred number of flights at all but four airports -- Chicago O'Hare, NY-John F Kennedy, NY-La Guardia, and Washington National -- where the

FAA set a cap on hourly departures. Since these airports have low HHIs, our estimated coefficients on concentration might be biased downwards since these airports might have been more congested were it not for the departure caps. We examine this possibility in column (5) of Table 3, part II by excluding all flights originating or departing from one of the four slot constrained airports. As expected, the coefficients on concentration increase appreciably from those in column (4), but the overall conclusions remain the same. For example, an increase in the HHI from 0.40 to 1.0 leads to a 1.9 to 2.3 minute decrease in excess travel time, still much smaller than the difference in excess travel time between a non-hub to a large hub carrier.

Further exploration:

The results in Table 3 suggest that hub carriers are willing to accept substantial delays on their own flights, even at airports where they control a large proportion of the total flights. We investigate the reasons behind these delays and the robustness of these results using more detailed data beginning in 1995 that allows us to track the movement of individual aircraft and to decompose overall travel time into time spent taxiing out to the runway, in the air, and taxiing in to the gate at the destination.

To begin, we consider the possibility that increased hub airline delays at the origin airport relative to the destination are due to late arriving aircraft from previous flights, so called "cascading" delays. If an aircraft is more likely to be delayed arriving at a hub, then it may be more likely to be delayed on departure, potentially leading us to double count delays. In this case, controlling for late arrivals in our regressions would reduce the estimated effect of hubbing on departure delays. However, this logic assumes that scheduled connection time is the same for hub and non-hub airlines. In our model, hub airlines have longer average layover time than non-hub carriers at the same airport. (Hub flights arrive in periods 0 and 1 and depart in period 2, while non-hub flights arrive and depart in the same period.) In addition, hub airlines face additional costs from late arrivals due to potential missed connections. With a longer average scheduled layover, or buffer, at their hub, a hub airline could still turn around a delayed aircraft and have it depart on schedule, mitigating cascading delays from late-arriving flights.

As it turns out, hub carriers do schedule longer times on the ground for their aircraft at their hubs. For flights after 1995, we use data on the aircraft tail numbers to compute a variable called "scheduled buffer," defined as the difference between the scheduled arrival time of the airplane from its previous flight and its next scheduled departure time. Table 4 reports the median number of minutes of scheduled buffer, broken out by whether the flight was on a hub carrier and the size of the hub.[26] The median scheduled time on the ground is 40 minutes at airports where there is no hubbing. Non-hub carriers at hub airports schedule somewhat longer buffer times, ranging from 45 to 50 minutes. Hub carriers, however, schedule yet longer buffers, ranging from 47 to 56 minutes. The scheduled buffer for hub carriers, and the difference between hub and non-hub carriers for a given airport hub size, increases with hub size.

To see how this extra padding on the ground affects our delay results, we repeat our estimation controlling for the actual buffer, which is the scheduled departure time minus the actual arrival time. This definition of buffer measures the *actual* time the plane has to be "turned around" once at the gate, thus taking into account both the scheduled buffer from the previous table and also the likelihood that the flight will arrive late. Given that hub flights have longer

[26]We use median scheduled time on the ground rather than the mean in order to reduce the skewness caused by planes parking at the airport overnight. To this end, in Table 4 we also exclude all observations with a buffer of three hours or more.

scheduled buffers, but are more likely to arrive late, the expected impact of controlling for the actual buffer on hub delays is unclear.

In Table 5 we present the same base regression with fixed effects from column (4) of Table 3 with the addition of spline terms for various levels of buffers: greater than 120 minutes, 41 to 120 minutes, 21 to 40 minutes, 1 to 20 minutes, 0 to −120 minutes, and less than −120 minutes.[27] The last two categories reflect aircraft that arrived after their next scheduled departure. The first column includes the base regression with the spline terms, and the second column is the base regression run only on the 1995 to 2000 sample period for comparison. Since the buffer variable is flight-specific, we use flight-level data rather than the cell aggregates in Table 3. Due to computer memory limitations, we use a random sample of 40 percent of the flights on Fridays.

The results in Table 5 suggest that while a late arrival is a good predictor of whether an aircraft departs late, it does not explain the excess delays created by hubbing. In fact, comparing columns (1) and (2), when we control for the buffer the hub airline coefficients nearly double in size and significance. This result implies that the congestion faced by hub airlines at hub airports relative to non-hub airlines is greater than was reported in Table 3. However, only some of that congestion manifests itself in passenger delays since the hub airline partially offsets it by scheduling longer layovers than non-hub airlines.[28]

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[27]We allow the kinks in the spline function to be discontinuous by adding indicator variables for each interval. To conserve space, we only report the estimated slopes on the spline function. There is very little difference, either qualitatively or statistically, if we force the function to be continuous.

[28]When we decompose excess travel time into its various components, a procedure which is described below, we find that controlling for buffer only increases the measured hub effect on

The coefficients on the buffer spline terms are all of the expected sign and significance. The coefficient on each spline term is interpreted as the marginal impact of an aircraft arriving a little later within a given buffer time period on the departure time of the aircraft on its next flight. The results show that buffer has little additional impact on flights already arriving more than 40 minutes before their next departure. Airlines can make up about one-half of additional delay (1 - 0.551) when aircraft arrive between 21 and 40 minutes prior to the next scheduled departure by turning the aircraft around quickly, but travel time increases about one-for-one (1.048) for flights whose inbound aircraft had a buffer of less than 20 minutes. The fact that delays do not increase one-for-one for the latest arriving category, more than 120 minutes late, may be due to airlines deciding to either cancel or substitute another aircraft for some very late flights.

The airport concentration effects are much lower in both specifications that use the 1995 to 2000 sample period. With fixed effects, the coefficient on concentration is identified only by changes in concentration within airports over a six year period. While there were many significant changes in concentration and hubbing within airports between 1988 and 2000, most of those changes had already taken place by 1995, leaving little variation with which to identify the concentration coefficient.

To further examine the robustness of our findings regarding hubs, we decompose excess travel time into its various components, including delay in departure from the gate, time spent taxiing to the runway, travel time mid air, and taxi time to the gate at the destination airport. As with total travel time, each component is measured as the excess from the minimum observed on

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delays in pushing back from the gate. The effect of hubbing on the other portions of the flight (taxi out time, flight time, and taxi in time) is unchanged to within one second. We take this as strong evidence that our interpretation of the buffer mechanism is correct.

the route during the month. (The minimum departure delay is imposed to be zero.) To the extent that the delays on hub carriers are due to hubbing, we should be able to isolate these effects at the origin and destination airports.[29]

Table 6 contains regression results using these four dependent variables in our base specification, with all data aggregated into cells. Given that the short time period with the airport dummies makes it difficult to identify airport level effects, we will focus on the within-airport hub airline coefficients. The results are consistent with the network benefits view of delays. For hub carrier flights originating at their hub, most delays involve a late departure from the gate or increased time on the taxiway, with the same increasing delays with hub size that we saw in Table 3. In fact, the sum of hub airline coefficients in column (1) for departure delay and column (2) for taxi out time is nearly exactly equal to our total estimated delay for flights originating at a hub in Table 5, column (2). Originating at a large hub accounts for 30 percent of the average departure delay and 17 percent of the average excess delay waiting to take-off. Originating at a

[29]Several seminar participants and a referee have suggested that variation in speed among aircraft types may explain some of the differences in travel time relative to minimum travel time on various routes. We provide two responses. In Table 6, we show that most hubbing related delays occur on the ground at either the origin or destination airport, casting doubt on the likelihood that differences in aircraft types flown by hub and non-hub carriers can explain these results. In addition, we have estimated the specifications in Tables 3 and 6 controlling for route distance, aircraft type, and distance interacted with aircraft type. These added covariates reduce the estimated magnitudes somewhat, but the qualitative and statistical conclusions remain the same. In particular, the estimated excess taxi in times, taxi out times, and departure delays at the largest hubs decline only about 10 percent but the excess flying time falls from 1.3 minutes to 0.13 minutes when traveling to the hub airline's largest hub, and from 1.3 minutes to 0.70 minutes when traveling to a 46-70 destination hub. Since the distances hub carriers fly and the aircraft types they use at their hubs are choice variables, we suspect that at least some of the differences are due to these variables capturing some delay that is actually caused by the hubbing process.

hub has virtually no effect on excess flying time or time spent on the taxiway at the destination airport.

Airline flights to their own hub require about a minute more time mid air, possibly due to air traffic queues into the hub airport. Arriving hub flights also have two minutes longer excess taxi times to their gates, accounting for one-half of the average, with the delays increasing with the size of the hub. Once again, flying to a hub does not affect delays at the origination airport as the departure delays and taxi out time effects are almost always indistinguishable from zero.

These regressions help highlight the sources of hub delays. Inbound hub aircraft spending additional time on the taxiway after landing could be due to congestion on the taxiway or time spent waiting for a gate to become available. In addition to queuing for the runway, excess departure delays and taxi out time at hubs might also reflect such congestion as the "alleyways" between gates being blocked by other departing aircraft. All these factors are examples of limited airport capacity leading to congestion that would affect hub airlines more than non-hubs.

Our final set of specifications in Table 7 takes an alternative approach to estimating differences in travel time for departing and arriving flights. The results in Table 3 suggest that flights originating at a hub have about 3 minutes longer excess travel times than flights arriving at hubs, no matter what the size of the hub. To examine these findings further, we rely on an identification approach similar to that in Borenstein (1991) in which he compares fares for flights on a given route arriving and departing from a carrier's own hub. We compute the difference in average travel time for departures versus arrivals on each route for each airline. These differences in travel time are regressed on variables for whether the origin airport was a hub, whether the flight was on an airline that hubbed at the origin airport, and the concentration at the origin airport. The coefficients on these variables can be interpreted as differences in the travel time for departures versus arrivals for each of the control variables.

The results in Table 7 show that the hub airline requires about 3 minutes longer travel time for flights originating at their own hub versus flights arriving at their hub, nearly exactly the same estimated difference between origin and destination travel time in Table 3, part II. The coefficients for the hub airline are little changed based on whether we use differences in total travel time or travel time above the minimum, or whether or not we include controls for route distance and direction. The latter controls are included to account for the possibility that the average hub is located in places where originating flights are systematically faster (or slower) due to natural weather or wind patterns. Differences in excess travel time for flights arriving or departing at hub airports (but not on the hub airline) and at concentrated airports are much smaller and not nearly as stable, suggesting that there are very few asymmetries in origin versus destination travel time when not traveling on the hub carrier.

5. Conclusion

Over the last 13 years, air traffic delays have grown considerably. From a policy perspective, it is important to distinguish between the two potential causes of delays: network benefits from hubbing, which lead hub carriers to accept higher equilibrium levels of delays, and congestion externalities, which cause higher delays for all carriers at an airport. Although we find evidence that congestion externalities lead to modest levels of air traffic delays, our results suggest that hubbing is the primary economic contributor to air traffic congestion. Flights departing from hub airports require between 4 and 7 minutes of excess travel time, while flights arriving at a hub require 1.5 to 4.5 minutes of additional delay. However, nearly all of the delays associated with hubbing are incurred by the hub airline itself. Non-hub airlines operating at hub airports face minimal delays at all but the largest hubs. Within hubs, delays increase monotonically with the size of the hub and flights originating at the hub face greater delays than flights arriving at a hub. All of these findings are consistent with a model in which the hub carrier receives large network benefits that increase with the number of markets served from a hub. These interconnection benefits encourage the hub carrier to bunch its flights at hubbing times, even at the cost of additional delays to its own flights.

From a social perspective, our findings also suggest that the imposition of a Pigouvian tax or arbitrary caps on airport takeoffs and landings that do not account for the network benefits of hubbing might result in social losses. In the presence of hubbing, the optimal policy does not just minimize delays without considering interconnection benefits. Delays are not necessarily evidence of a socially inefficient outcome, but in many cases might reflect the optimal use of scarce runway capacity by hub airlines trying to provide consumers with a large variety of potential destinations and relatively short connection times. With a very high market share during peak hubbing times when most delays occur, dominant hub carriers already appear to internalize an appreciable portion of the congestion costs at their own hub airports. While hub carriers may impose a cost on non-hub airlines by crowding them out of certain flight times, a social planner who recognized the network benefits from hubbing might also choose a similar outcome.[30] Also, not all of the costs of hubbing show up in delays. Hub airlines schedule longer layovers for their aircraft at their hubs, at a cost of having their planes sit idle, but reducing the extent of passenger delays. These costs, too, are internalized by hub carriers.

To some degree, our finding of a small congestion externality effect reflects the fact that the four airports most likely to suffer from it -- La Guardia, JFK, Washington National and Chicago O'Hare -- already face FAA limits on the number of hourly flights at the airports. Indeed, our measured congestion externality effect increases when we exclude these airports from the estimation. In addition, in a well-publicized policy shift, the FAA recently removed the hourly caps on service at La Guardia, an airport that has a low concentration, no single dominant hub carrier, small capacity, and large local demand. Airlines immediately moved in to increase service. Shortly thereafter, La Guardia accounted for about 25 percent of all delays of more than 15 minutes for the entire nation. This incident, along with our empirical results, suggests that congestion externalities are important at some airports, and would be more important were the FAA to remove the caps at any of the slot constrained airports. Congestion pricing may be an appropriate solution for the inefficiency at these airports.

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[30]These comments only relate to hub carrier choices relative to delays and do not measure the extent to which hub carriers have a high market share because they have successfully limited entry by other carriers. Debates over access to gates at the new airports in Denver and Pittsburgh suggest that market power over local passengers is an important consideration by airlines regarding their willingness to invest in additional capacity.

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Table 1: Summary Statistics

Variable	Percent of Total	Mean	Standard Deviation
Actual elapsed route time minus minimum + departure delay		30.4	14.9
Departure delay: actual push-back time minus scheduled departure		9.7	9.8
Taxi out time: time from push-back to wheels-off-the-ground minus minimum feasible time*		9.8	5.0
Actual flight time minus minimum feasible flight time*		16.1	9.4
Taxi in time: time from landing to reaching the gate minus minimum feasible time*		4.1	2.3
Origin airport concentration		0.40	0.21
Origin airport hub size:			
26 – 45 markets		0.17	0.37
46 – 70 markets		0.15	0.36
71 + markets		0.22	0.41
Origin airline hub size:			
26 – 45 markets		0.09	0.28
46 – 70 markets		0.15	0.35
71 + markets		0.15	0.36
Flight is traveling to or from a hub airport		0.83	0.38
Flight is traveling to or from the airline's own hub		0.74	0.44
Buffer: Minutes between actual arrival and scheduled departure, spline terms:			
< -120 minutes*	0.004	-173	63
0 and –120 minutes*	0.061	-29	27
1 and 20 minutes*	0.093	13	6
21 and 40 minutes*	0.191	31	6
41 and 120 minutes*	0.403	62	17
> 120 minutes*	0.249	652	343

Sample includes all flights for major carriers on Fridays from January, 1988 – November, 2000 (N=9,956,576), except for rows with (*) which include Fridays from January, 1995- November, 2000 (N= 4,592,595). Also, data is missing for July and August, 1993, March, 1994, and May, 1999. For rows 3-5, minimum feasible time is route and direction specific and is computed as the shortest amount of time required for a flight on a given route and month to taxi-out, fly the route and taxi-in, respectively.

Table 2a: Hubbing and concentration for airports with at least one percent of flights in November, 2000

		Hub carriers with...		
Airport	Airport Concentration	71+ connections	46-70 connections	26-45 connections
Atlanta	0.72	Delta		
Baltimore-Washington	0.29			Southwest
Charlotte	0.81		USAirways	
Chicago O'Hare	0.38	United	American	
Cincinnati	0.91		Delta	
Cleveland	0.31			Continental
Dallas-Forth Worth	0.52	American		Delta
Denver	0.57		United	
Detroit	0.63	Northwest		
Houston Intercontinental	0.61	Continental		
Las Vegas	0.25			America West, Southwest
Los Angeles	0.19			American, United
Memphis	0.66			Northwest
Miami	0.37			American
Minneapolis-St. Paul	0.66	Northwest		
Nashville	0.31			Southwest
Newark	0.38		Continental	
Philadelphia	0.50		USAirways	
Phoenix	0.30		America West	Southwest
Pittsburgh	0.81		USAirways	
Saint Louis	0.52	Trans World		
Salt Lake City	0.48		Delta	
San Francisco	0.33			United
Washington Dulles	0.39			United
Washington National	0.23			USAirways

Airports with at least one percent of flights in November 2000 but without a large hub carrier are (concentration in parentheses): Boston (0.29), Chicago Midway (0.71), Houston Hobby (0.84), LaGuardia (0.22), Kansas City (0.23), Oakland (0.47), Orlando (0.19), Portland (0.19), San Diego (0.21), San Jose (0.24), Seattle (0.23), Tampa (0.18)

Table 2b: Hubbing and concentration for airports with at least one percent of flights in November, 1988

Airport	Airport Concentration	Hub carriers with... 71+ connections	46-70 connections	26-45 connections
Atlanta	0.43	Delta	Eastern	
Baltimore-Washington	0.47			Piedmont
Charlotte	0.80		Piedmont	
Chicago O'Hare	0.40	United	American	
Cincinnati	0.54		Delta	
Dallas-Forth Worth	0.44	American	Delta	
Denver	0.38		Continental United	
Detroit	0.45		Northwest	
Houston Intercontinental	0.51		Continental	
Memphis	0.63		Northwest	
Minneapolis-St. Paul	0.60		Northwest	
Nashville	0.40			American
Newark	0.27			Continental
New York JFK	0.18			TWA
Orlando	0.17			Delta
Philadelphia	0.23			USAir
Phoenix	0.28			America West
Pittsburgh	0.69	USAir		
Raleigh-Durham	0.41			American
Saint Louis	0.61	Trans World		
Salt Lake City	0.62		Delta	
San Francisco	0.20			United
Washington Dulles	0.47			United

Airports with at least one percent of flights in November 1998 but without a large hub carrier are (concentration in parentheses): Boston (0.12), Cleveland (0.21), Houston (0.41), LaGuardia (0.12), Las Vegas (0.24), Los Angeles (0.13), Miami (0.19), San Diego (0.13), Seattle (0.16), Tampa (0.14), and Washington National (0.12).

Table 3, Part I: The Effect of Airline Hubbing and Airport Concentration on Travel Time

Dependent Variable: Travel Time in Excess of Minimum Feasible

	Whole Sample (1)		Whole Sample (2)		Whole Sample (3)	
	OLS		IV		OLS	
	Origin	Destination	Origin	Destination	Origin	Destination
Airport Hub Size						
26 to 45 markets	4.07 (0.26)	2.34 (0.28)	4.52 (0.19)	-0.31 (0.17)	-0.53 (0.23)	-1.01 (0.20)
46 to 70 markets	6.67 (0.33)	3.62 (0.34)	6.20 (0.22)	-0.85 (0.21)	1.93 (0.32)	0.82 (0.31)
71 or more markets	7.25 (0.42)	4.49 (0.42)	5.44 (0.15)	0.79 (0.14)	4.12 (0.36)	1.92 (0.35)
Airport Concentration	-6.38 (0.57)	-6.97 (0.60)	-4.82 (0.24)	-1.38 (0.24)	-1.29 (0.55)	-2.93 (0.54)
Airport Fixed Effects	No		No		Yes	
R-squared	0.24				0.34	
Number of Observations	617,150		617,150		617,150	

Notes: Robust standard errors in parentheses. Regressions are based on the mean of the dependent independent variables for each airline on every route for all months in every year. Equations also include indicator variables for year, month, and airline and various economic demand variables that are described in the paper.

Table 3, Part II: The Effect of Airline Hubbing and Airport Concentration on Travel Time

Dependent Variable: Travel Time in Excess of Minimum Feasible

	Whole Sample (4)		Whole Sample exc. Slot Constrained Airports (5)	
	OLS		OLS	
	Origin	Destination	Origin	Destination
Airline Hub Size				
26 to 45 markets	3.38 (0.34)	0.28 (0.35)	3.04 (0.34)	-0.0012 (0.35)
46 to 70 markets	5.24 (0.39)	1.97 (0.41)	4.61 (0.38)	1.38 (0.39)
71 or more markets	5.62 (0.45)	2.82 (0.46)	5.62 (0.48)	2.52 (0.45)
Airport Hub Size				
26 to 45 markets	-1.85 (0.27)	-0.87 (0.26)	-0.74 (0.26)	-0.11 (0.27)
46 to 70 markets	-0.79 (0.39)	0.07 (0.40)	0.74 (0.39)	1.25 (0.40)
71 or more markets	1.04 (0.47)	0.50 (0.47)	2.22 (0.49)	1.44 (0.48)
Airport Concentration	-1.73 (0.54)	-2.65 (0.54)	-3.24 (0.55)	-3.85 (0.54)
Airport Fixed Effects	Yes		Yes	
R-squared	0.34		0.34	
Number of Observations	617,150		516,962	

Notes: Robust standard errors in parentheses. Regressions are based on the mean of the dependent independent variables for each airline on every route for all months in every year. Equations also include indicator variables for year, month, and airline and various economic demand variables that are described in the paper.

Table 4: Median Number of Minutes of Scheduled Buffer Between Aircraft Arrival and Departure:1995-2000

Airport hub size	Non-Hub Carrier	Hub Carrier
None	34	
26 to 45 markets	40	42
46 to 70 markets	44	49
71 or more markets	38	54

Notes: Includes all flights with a scheduled buffer of 3 hours or less in order to exclude aircraft that remain at an airport overnight. Based on a 2-in-5 sample of all flights on Fridays.

Table 5: The Effect of Late Arriving Aircraft on Excess Travel Time Due to Airline Hubbing and Airport Concentration: 1995-2000

Dependent Variable: Travel Time in Excess of Minimum Feasible

	(1)		(2)	
	Origin	Destination	Origin	Destination
Airline hub size				
26 to 45	3.48 (0.11)	0.01 (0.11)	1.02 (0.14)	0.39 (0.15)
46 to 70	7.45 (0.12)	4.57 (0.12)	2.55 (0.17)	2.80 (0.17)
71 or more	9.15 (0.12)	6.49 (0.13)	2.15 (0.17)	3.04 (0.17)
Airport hub size				
26 to 45 markets	-2.79 (0.14)	-1.51 (0.14)	-3.41 (0.19)	-2.16 (0.19)
46 to 70 markets	-3.45 (0.23)	-0.68 (0.24)	-2.15 (0.32)	-0.76 (0.32)
71 or more markets	-3.15 (0.27)	-1.71 (0.28)	-0.39 (0.37)	0.04 (0.38)
Airport concentration	-0.07 (0.70)	-2.37 (0.66)	-1.82 (0.96)	-2.51 (0.91)
Buffer size				
Less than – 121 minutes	-0.771 (0.006)			
0 to – 121 minutes	-1.027 (0.003)			
0 to 20 minutes	-1.053 (0.010)			
21 to 40 minutes	-0.626 (0.007)			
41 to 120 minutes	-0.019 (0.002)			
More than 120 minutes	0.027 (0.008)			
R-squared	0.51		0.07	

Notes: Robust standard errors in parentheses. Regressions also include indicator variables for year, month, airport, and airline and various economic demand variables that are described in the paper. Based on a 2-in-5 sample of all flights on Fridays. (N= 1,782,601)

Table 6: Decomposing Delays to Identify the Effects of Hubbing on Various Measures of Travel Time: 1995-2000

	(1)		(2)		(3)		(4)	
Dependent Variable:	Departure Delay		Taxi Out Time		Flight Time in Excess of Minimum Feasible		Taxi In Time	
	Origin	Destination	Origin	Destination	Origin	Destination	Origin	Destination
Airline hub size								
26 to 45 markets	2.15 (0.18)	0.057 (0.20)	1.21 (0.12)	-0.59 (0.11)	-0.77 (0.41)	-0.38 (0.41)	0.05 (0.07)	0.41 (0.07)
46 to 70 markets	2.80 (0.20)	-0.12 (0.21)	1.58 (0.16)	-0.76 (0.14)	0.19 (0.48)	1.24 (0.47)	-0.30 (0.08)	1.38 (0.08)
71 or more markets	3.15 (0.24)	0.21 (0.21)	1.65 (0.17)	-0.78 (0.16)	0.13 (0.47)	1.21 (0.48)	-0.03 (0.09)	1.94 (0.10)
Airport hub size								
26 to 45 markets	-0.99 (0.17)	-0.59 (0.17)	-1.37 (0.12)	-0.08 (0.11)	-0.30 (0.26)	-0.38 (0.30)	-0.05 (0.05)	-0.37 (0.05)
46 to 70 markets	-0.82 (0.25)	0.41 (0.27)	-0.20 (0.21)	-0.0005 (0.20)	-1.38 (0.41)	-0.03 (0.40)	0.04 (0.08)	-0.57 (0.08)
71 or more markets	0.060 (0.29)	0.51 (0.30)	0.001 (0.24)	-0.04 (0.22)	-1.28 (0.49)	-0.04 (0.49)	-0.21 (0.10)	-0.90 (0.10)
Airport concentration	-0.18 (0.37)	-0.71 (0.37)	-0.14 (0.34)	-0.47 (0.39)	-2.58 (0.98)	-2.95 (1.02)	-0.07 (0.17)	0.60 (0.13)
R-squared	0.17		0.57		0.30		0.64	

Notes: Robust standard errors in parentheses. Regressions are based on the mean of the dependent independent variables for each airline on every route for all months in every year. (N= 262,285 airline-route-month/year cells) Equations also include indicator variables for year, month, and airline and various economic demand variables that are described in the paper.

Table 7: Difference between Time Required for Outbound and Return Flights on all Airline Routes

Dependent Variable:	Difference in (Travel Time in Excess of Minimum Feasible)		Difference in (Total Travel Time)	
	(1)	(2)	(3)	(4)
Airline hub size (at origination)				
26 to 45 markets	3.17 (0.08)	3.11 (0.08)	3.84 (0.13)	3.49 (0.08)
46 to 70 markets	3.04 (0.08)	3.08 (0.07)	2.52 (0.12)	2.72 (0.07)
71 or more markets	3.02 (0.09)	3.07 (0.08)	3.08 (0.13)	3.18 (0.18)
Airport hub size (at origination)				
26 to 45 markets	-0.02 (0.07)	0.15 (0.07)	-0.93 (0.11)	0.10 (0.06)
46 to 70 markets	0.43 (0.09)	0.05 (0.08)	0.44 (0.13)	-0.98 (0.08)
71 or more markets	0.23 (0.09)	-0.28 (0.08)	-0.39 (0.12)	-2.26 (0.08)
Airport concentration (at origination)	-0.25 (0.10)	-0.37 (0.10)	0.62 (0.14)	0.52 (0.10)
Direction, time & distance interactions	No	Yes	No	Yes
R-squared	0.05	0.11	0.02	0.06

Notes: Robust standard errors in parentheses. Regressions are based on the difference between the mean time for outbound and return flights for each airline on every route with bi-directional service in a month. (N= 303,100 airline-route-month/year cells) Direction, time, and distance interactions include a dummy variable for direction (north, south, east, west) interacted with a dummy variable for each month interacted with variables equal to distance between route airports and distance squared (4*12*2= 96 additional variables).

Figure 1: Hub versus airport's total flights at Dallas-Fort Worth (DFW)

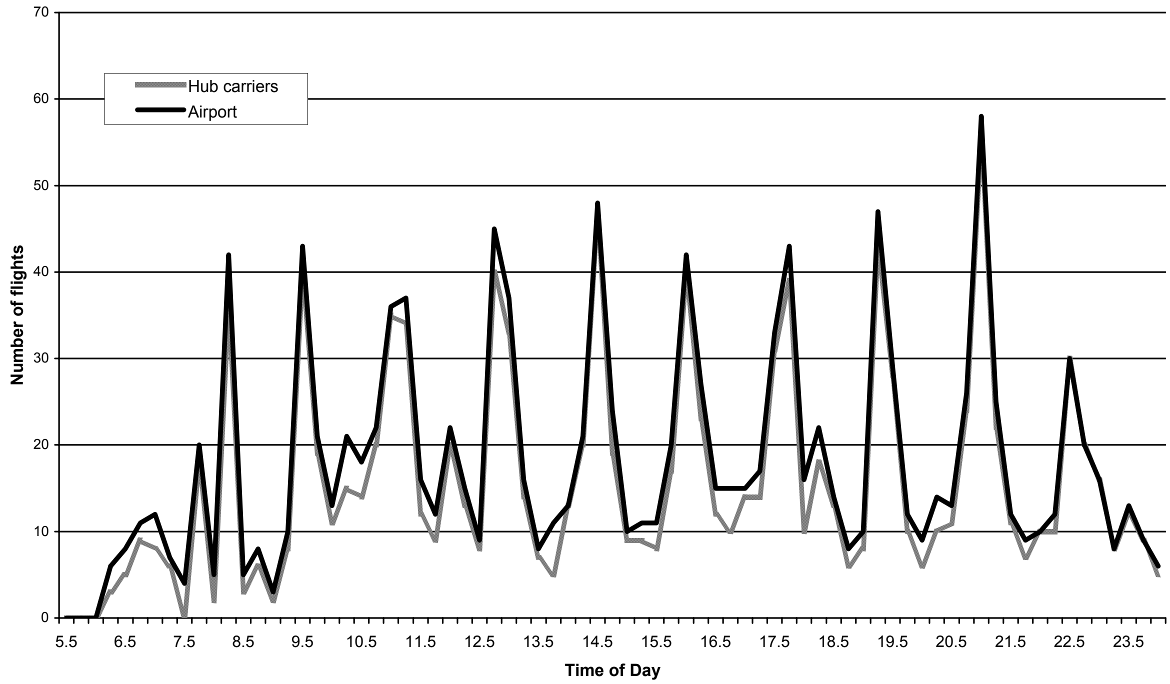

Figure 2: Hub carriers' departures and arrivals at Dallas-Fort Worth (DFW)

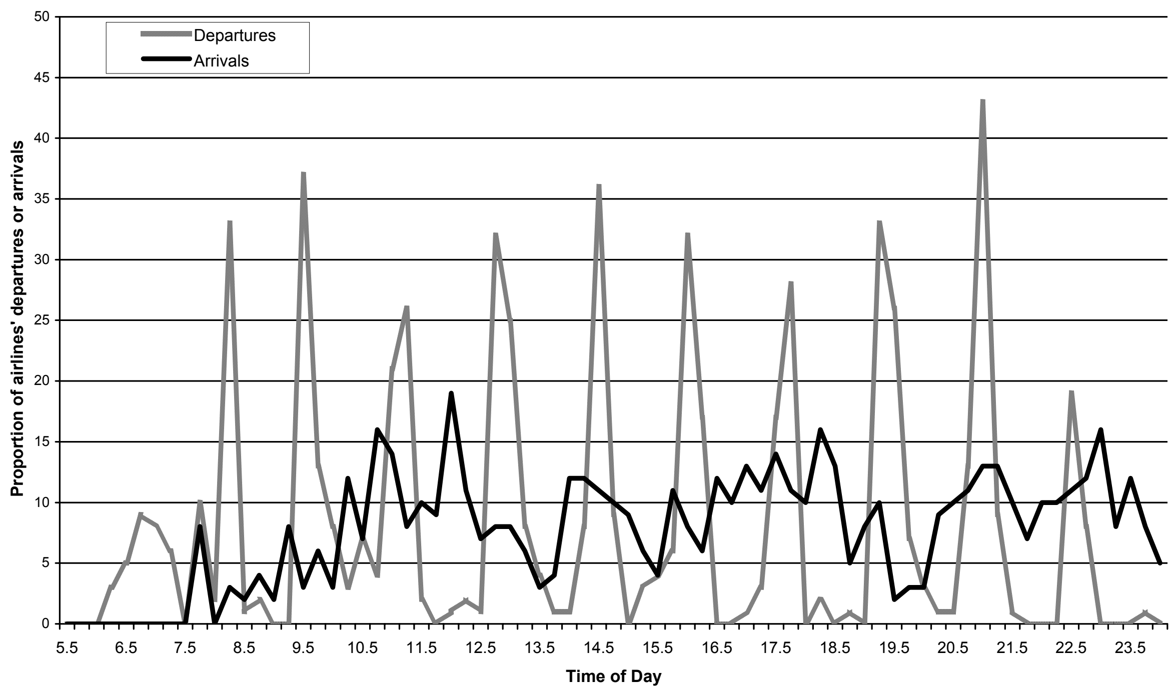

Figure 3: Total flights at Boston Logan Airport (BOS)

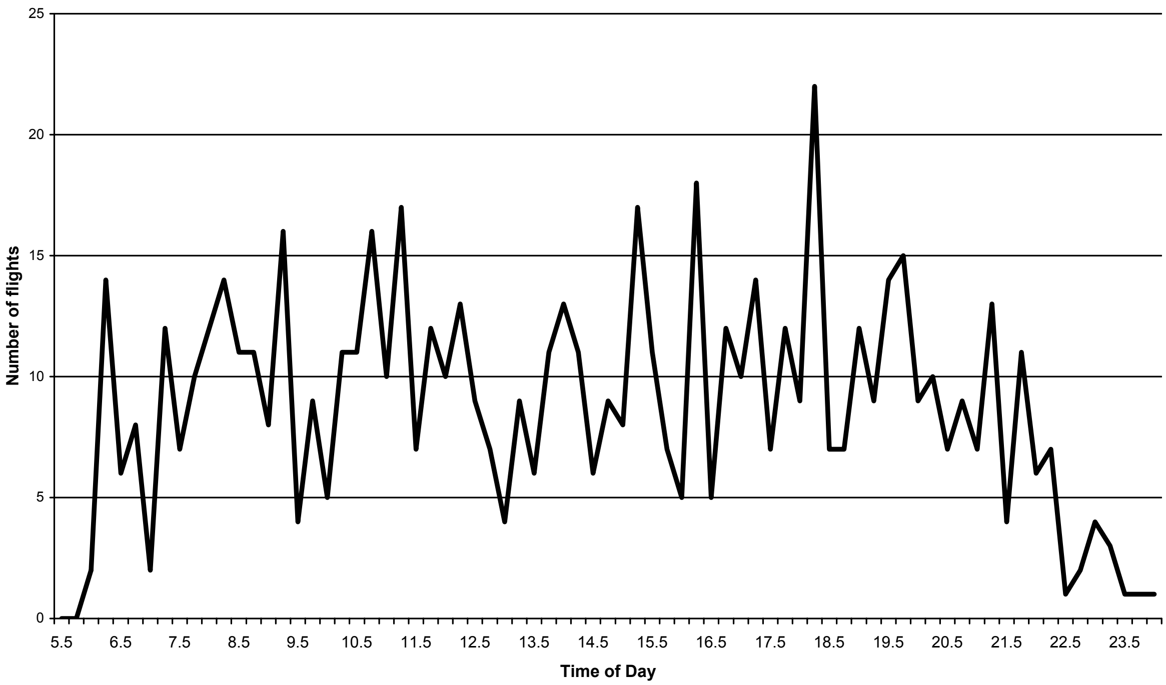

Figure 4: Departure density for hub and non-hub carriers at Dallas-Fort Worth (DFW)

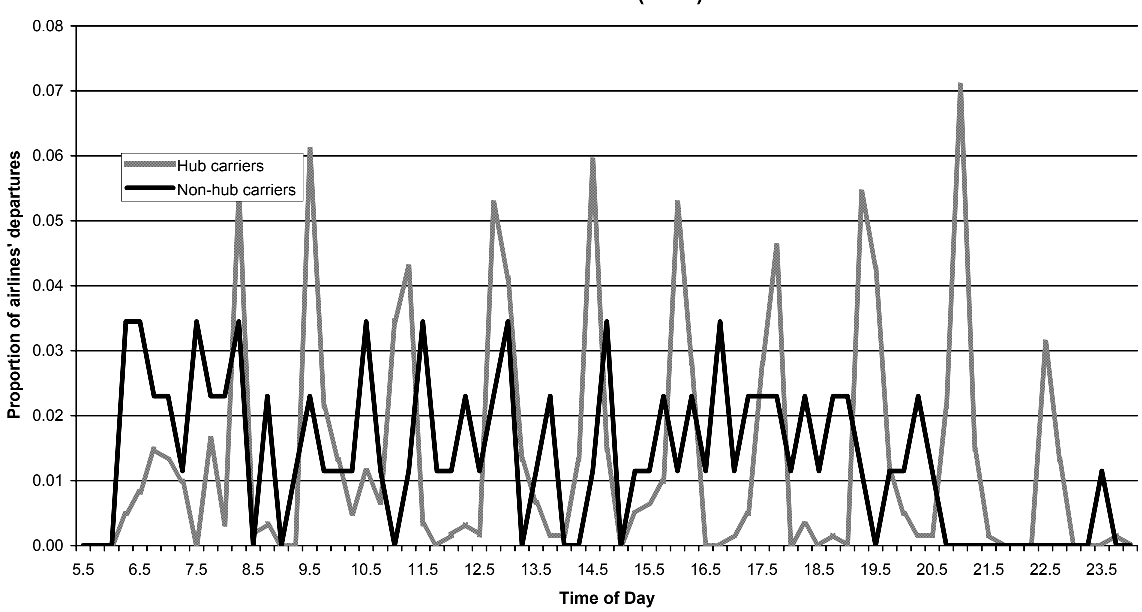

Figure 5: Minimum, Scheduled, and Actual Travel Times