Departure Delays, the Pricing of Congestion, and Expansion Proposals at Chicago O'Hare Airport

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Published in the *Journal of Air Transport Management*,
Volume 12(4), pages 182-190 (July 2006).

Abstract

Chicago's O'Hare airport is extremely congested, especially in the late afternoon and early evening. The paper uses a publicly available database to estimate the relationship between the number of flights wishing to depart and the delays they experience. This relationship is used to calculate congestion fees that provide airlines with incentives to move some flights out of the peak period and to slightly alter the scheduled departure time of other flights to avoid the rush of departures that occur on the hour. The very high fees at certain times of day point to the benefits that can be obtained from current plans to expand and reconfigure the airport to reduce delays in both good and bad weather.

1. Introduction

Chicago's O'Hare International Airport suffers from considerable congestion. It is a major hub airport for both United Airlines and American Airlines. Despite the downturn in traffic and flights after the terrorist attacks of September 11, 2001, and the filing for bankruptcy protection by United Airlines in December 2002, delays have got worse rather than better. The abolition in July 2002 of slot controls, which limited the number of flights in any given hour, led to an increase in flights particularly in the late afternoon and early evening. Capacity became

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further strained by the introduction of regional jet aircraft that share the runways with mainline jets, whereas the turboprops they replaced could use other, shorter, runways.

The situation became so bad that in the summer of 2004 the U.S. Department of Transportation brokered a deal whereby the two dominant airlines agreed to move 37 flights out of the peak hours to earlier or later in the day. In addition, slot controls were temporarily reintroduced in November 2004 that limit domestic arrivals to 88 per hour between 7am and 8pm. In the period between July 2002 and November 2004, arrival rates peaked at 120 flights an hour. In the longer term, there is a $14.8 billion plan to build new runways and reconfigure some of the existing ones. This will create an airport with parallel runways rather than intersecting ones. The plan will increase the airport capacity and alleviate the need to reduce operations in particular wind conditions.

Economists argue that the problem at O'Hare is exacerbated by weight-based landing fees that do not vary by time of day. This fee schedule does not give airlines the correct incentives to schedule their flights outside of the most congested periods or to use larger aircraft to consolidate multiple departures to the same destination. This paper makes use of a publicly available government data set detailing actual flight operations to investigate departure delays, the structure and magnitude of optimal pricing, and hence the benefits from the O'Hare modernization plan. The available data do not allow for comparable calculations to be made for arriving flights.

2. Dealing with Airport Congestion

Chicago O'Hare is hardly alone in its struggle to manage capacity. Khan (2001) reports that 120 airports worldwide face some form of capacity constraints that require airlines to coordinate their schedules. Ordinarily, this is accomplished in biannual schedule coordination conferences held under the auspices of the International Air Transport Association (IATA). Some of these airports, including Chicago O'Hare, are severely congested. A recent National Economic Research Associates (NERA, 2004) report indicates that 21 airports within the European Union are operating at capacity for at least part of the day and seven are at capacity throughout the day. In the United States, four airports are sufficiently congested that slots are, or were, rationed by the federal government.

In both Europe and the United States, the allocation of slots when potential demand outstrips capacity is based on historical precedence. Provided that the airline actually makes use of its slots, it retains "grandfather rights" to them. For international flights, some governments have bilateral agreements specifying the availability of a certain number of slots at particularly congested airports. Within the European Union (EU), the allocation of slots is guided by Regulation 793/2004 (an April 2004 amendment to the existing decade-old Regulation 95/93). These regulations give particular emphasis to making sure that unused slots are made available for new entrants rather than becoming monopolized by the dominant carrier(s) at the airport.

The common feature of the IATA coordination conferences, the United States slot controls, and the EU regulations is that they deal with the allocation of slots between airlines and not with the landing fees associated with making use of the slots. In general, landing fees for international flights are governed by the International Civil Aviation Organization's (ICAO) *Policies on Charges for Airports and Air Navigation Services* which state that charges should not exceed the full cost of facilities and services (including a return on capital) provided at the airport. ICAO also specifies that landing fees should not discriminate between international and domestic flights, effectively meaning that the ICAO policy document also determines the fees charged for domestic flights. Inherently, the ICAO rules limit the role of landing fees to recovering actual out-of-pocket airport expenses and do not allow price to be used as a method of dealing with excess demand and allocating scarce capacity.

Consequently, the landing fees at any given airport do not generally vary between different times of the day based on the level of demand. While NERA (2004) reports that six airports in the EU do have slightly higher posted fees in peak periods, the experience both in Europe and the United States with using peak pricing to relieve congestion has been very disappointing (Schank, 2005). The combined opposition of the airlines and the general aviation community has discouraged most airports from attempting to implement peak pricing systems.

That said, even if slots are allocated based on historical precedence and the posted landing fees are not higher in the peak, some element of peak pricing will emerge if airlines can trade slots between themselves (so called "secondary trading'). Airlines holding peak period slots might be tempted to sell them at a price premium to other carriers. While this practice is allowed in the United States, the EU regulations discourage this. In general, EU airlines can only swap slots on a one-for-one basis, albeit that there may be some "side payment" if one slot is considered more valuable than another. It is also fair to say that the amount of slot trading observed in practice is relatively limited (Starkie, 1998).

In a significant departure from past practice, the EU commissioned NERA to produce a report on possible market mechanisms for allocating slots. NERA (2004) investigated a number of possible options, including raising the posted landing fees to reflect the level of congestion, permitting a legal secondary trading market for slots, and using auctions rather than historical precedence to initially allocate slots. The latter would build on the recent international experience in allocating broadcasting and telecommunications licenses, where capacity is limited by the radio spectrum. NERA concluded that "a combination of higher posted prices and secondary trading might have the greatest potential of any of our options to achieve the allocation of slots under the ideal market mechanism."

This current paper contributes to the debate by estimating the magnitude of the higher posted landing fees that would have to be implemented at Chicago O'Hare to reflect the congestion caused by scheduling additional departures at peak times.

3. The Steady-State Bottleneck Congestion Model

The paper employs the steady-state bottleneck congestion model that is commonly used for highways (Walters, 1961). It is a steady-state model in that we do not attempt to model how demand functions may endogenously shift when congestion-based pricing produces landing fees that vary dramatically by time of day. Such endogeneity can only be achieved by using simulated models of airline operations such as those in Daniel (1995) and Daniel and Pahwa (2000). In contrast to these papers, our calculations are much simpler and more transparent. This paper does provide some insight into the magnitude of congestion fees applicable at a highly congested facility. Daniel used Minneapolis-St Paul as his empirical example, which is less congested and features "banks" of flights associated with hub-and-spoke operations that are interspersed by periods of light demand. In contrast, O'Hare has many hours of continuous congestion.

The paper treats the entire airfield, excluding the gates, as a bottleneck. While the root cause of the congestion is that only one aircraft can occupy a runway at a given time, the congestion is manifested on the taxiways leading to the runways. The model is shown in Figure 1. On the horizontal axis is the density of aircraft wishing to take off at time t, which can be visualized as a snapshot photograph of the number of aircraft on the airfield which have pushed back from the gate but have yet to take off. In the remainder of the paper, we will refer to the "departure queue" which is synonymous with density. The vertical axis is the generalized cost of the taxi-out time, which we will define as the time between push back and wheels leaving the runway. The cost is a function of the taxi-out time and is a combination of the operating costs to the airline and the passengers' time costs.

The average variable cost (AVC) curve represents the "private" costs incurred by a specific aircraft and its passengers for different lengths of the departure queue. Absent congestion, there is a minimum time that is necessary for a flight to back away from the gate, taxi to the appropriate runway, and immediately take off. While this will depend on the proximity of the gate and the assigned runway, at O'Hare this minimum time is about ten minutes. If there are relatively few aircraft in the departure process, the taxi-out time will not increase from this average of ten minutes because by the time an aircraft arrives at its assigned runway, the previous aircraft has already departed. However, at some point the rate of aircraft pushing back from the gate exceeds the capacity of the runways, and a queue starts to develop. In addition delays are experienced maneuvering in the gate areas and waiting at intersecting taxiways. The taxi-out costs will continue to increase as more aircraft wish to depart.

At some airports, such as those with only one runway, there is an added complication that there are two competing sets of traffic merging into the bottleneck. The rate of arriving aircraft will affect the wait experienced by departing aircraft. At O'Hare this is not an issue as they have some runways dedicated exclusively to arrivals and others dedicated exclusively to departures. Of course, arriving and departing aircraft do interact when taxiways intersect and there may be congestion around the gates. However, analysis of our data found that taxi-out time was invariant with the arrival rate experienced at the time an aircraft pushes back.

The marginal cost (MC_1) of an additional aircraft will increase quicker than the private (AVC) cost because not only are the private costs of the $(n+1)^{th}$ aircraft higher than those of the n^{th} aircraft, but this additional aircraft will also slow down the departure of other aircraft who are behind it in the queue. For example, consider an aircraft that has reached the front of the queue and has nineteen aircraft waiting behind it. Had the aircraft not wished to depart, each of the following aircraft would have experienced a queue that was one shorter than it actually was.

At O'Hare the effects can extend far beyond the aircraft that are in the queue at the point the marginal aircraft takes off. Congested conditions exist continually from 3pm in the afternoon until 8:45pm in the evening. Consequently, the aircraft we discussed in the previous paragraph will also make the queue longer by one for all aircraft that have yet to leave the gate up until the time that congestion dissipates. The costs incurred by this second group of flights are represented by the vertical distance between MC_1 and a second marginal cost function (MC_2). For a flight toward the end of the congested period (say at 8pm), the difference between MC_1 and MC_2 will be quite small. However, for a flight earlier in the congested period (say at 4pm), the difference will be very large.

For a fixed capacity (that is, a fixed number and configuration of runways), the standard economic model suggests that, in the short run, society maximizes welfare when the price of a good equals its marginal cost. Figure 1 also shows two demand functions for air travel at times t1 and t2. Time t1 represents a situation where a queue has developed. When there is no congestion pricing, airlines will equate their demand with their private costs. That is the intersection of the demand function t1 and AVC, shown as point A, where D_1 aircraft will wish to depart. However, the optimal queue length is at D_2 where demand function t1 intersects MC_2.

At this point the marginal cost exceeds the private cost by distance EG. This is composed of EF imposed on aircraft already in the queue at time the marginal aircraft takes off and FG imposed on aircraft yet to leave the gate. A congestion price of EG will produce an optimal number of flights. (Technically, we are assuming that price changes are not so severe that they significantly reduce the effective real income of airline passengers and shift the demand function.) At low demand times, such as represented by t2, when the demand function intersects the horizontal portion of the AVC curve, no congestion fee is payable.

However, Brueckner (2002a,b, 2005) points out that there is an important modification that needs to be made to the highway model to make it applicable to airports. In the highway model, users are "atomistic" in that, absent pricing, they make decisions on traveling ignoring the effects of their decision on all other highway users. In contrast, at most airports, one or two airlines dominate operations. A major airline adding a flight at a congested time will delay its own planes as well as those of other airlines. In deciding to add a peak flight, the airline will consider the delay that that specific flight will encounter and the increased delay to its other flights. The costs imposed on its other flights will be "internalized" by the airline. Moreover, Brueckner shows that an oligopolistic airline will internalize both the additional operational costs (fuel, aircraft utilization, staff costs) suffered by its other flights and the value of the additional travel time suffered by its passengers on those flights. This is because, in equilibrium, peak travel is now less attractive, and the airline would have to charge a lower fare to compensate. Consequently, a congestion price should only reflect delays imposed on other airlines and their passengers. Therefore the congestion fee charged to an airline should be calculated as (1-proportion of an airline's share of departures) multiplied by the distance EG.

4. Data

The first step in the analysis is to use regression techniques to estimate the equation of the AVC function in Figure 1. Data were obtained from a federal Bureau of Transportation Statistics airline on-time database showing the actual push-back time from the gate and the wheels-off time for all domestic flights. The queue length is found by calculating the number of aircraft (including itself) that at the moment of push back have pushed back but have not had wheels off. This is only an approximation of the departure queue as there are circumstances where an aircraft that pushes back later can "jump the queue," and other cases where an aircraft already in line for take off is taken out of the queue (perhaps due to a ground hold because of weather delays at the destination airport). We had considered measuring the departure delay from the time of scheduled departure rather than push back, but rejected this as we were interested in delays due to congestion rather than delays due to late arriving aircraft, mechanical problems, boarding problems or ground holds at the gate.

A caveat to the data is that it only covers domestic scheduled services. Therefore, there are no data on international departures by both foreign and U.S. airlines, cargo flights, private or chartered flights, or general aviation. We do not know the delays suffered by these flights. What is more important, we do not know the number of such flights in the departure queue.

Initially, analysis was conducted on the "recurrent" congestion that is due to an excessive number of flights being scheduled. Wednesday, September 22, 2004 was selected for analysis, as it was as close to perfect flying conditions as one could imagine in Chicago with clear to partly cloudy skies, no rain, and variable winds at less than ten knots. Similar moderate conditions were experienced elsewhere across the nation on that day limiting the necessity for weather-related ground holds. Later in the paper, a contrast will be drawn with the Wednesday of the previous week, September 15, when poor weather intervened. Both dates are prior to the reintroduction of slot controls in November 2004.

5. Relationship between Queue Length and Taxi-out Time in Good Weather.

Figure 2 shows a scatter plot of the observed taxi-out times plotted against queue length for the 1,021 domestic departures on September 22. The reader is reminded that the data only include domestic departures, so the actual queue length will be longer due to international, cargo and general aviation flights. There are two general observations. The first is that there is considerable variation in taxi-out times experienced by different aircraft for any given queue length. This is primarily because some gates are more distant from the assigned runway than others. Second, there are some outliers experiencing taxi-out times of 35 minutes or more, even when the queue is short. We checked to see if there was some commonality between the outliers that might provide an explanation. For example, these aircraft might have experienced ground holds after they left the gate due to congestion or weather problems at their destination. While many of the outliers involved flights to Newark and Washington Dulles, there did not appear to be any strong patterns. Some flights to the same destinations that departed a little bit earlier or later did not experience the delays. In addition, other outliers appear to be entirely random in terms of time of day and destination.

Overall, taxi-out times seem to average ten minutes when there are less than seven aircraft wishing to take off. Beyond seven aircraft, the taxi-out times begin to creep up to about 12 minutes when ten aircraft are in the queue and to 15 minutes when the queue is 20 aircraft. The delays start to increase quite rapidly when there are more than 25 aircraft in the queue. At 8pm, when the queue is the longest, there are 41 aircraft in the queue and the taxi-out time is about 25 minutes.

Regression analysis was used to estimate a relationship between queue length and taxi-out time. Visual inspection suggests that the desired functional form would have a positive intercept value for taxi-out time, a relatively flat portion when queue length is short, and then a greater-than-linear increase as the queue grows longer. Various functional forms were tested, and the one with the best fit was estimated as:

$$\ln(T) = \underset{(141)}{2.498} + \underset{(19)}{0.00051}\, D^2 + \varepsilon \qquad \text{Number of Observations} = 1{,}021, \quad \text{Adjusted } R^2 = 0.2233$$

where T is the taxi-out time, D is the queue length, and t statistics are shown in parentheses. This curve is plotted as the solid line in Figure 2.

6. Departure Congestion Prices for Good Weather

The engineering relationship estimated in the previous section can be transformed into Figure 1's private cost (or AVC) curve by knowing the cost of a minute of delay to the airline and its passengers. The Federal Aviation Administration's standard guidance for economic evaluation (GRA, 2004) recommends a value of passengers' time for all travel purposes of $31.37 per hour and total aircraft operating costs including both fixed and variable costs of $2,873 per hour for large ("Part 121") carriers, both in 2004 prices. The fixed costs of aircraft operation, such as insurance and aircraft leasing costs, are included in the calculation because one would expect that if delays were reduced then airlines could operate a smaller fleet. Information on total domestic September 2004 enplanements and departures at O'Hare reveals that there was an average of 86 passengers per plane. From these values, the total cost per minute of taxi-out time is estimated to average $92.97.

Consequently the atomistic AVC curve in Figure 1 will take the form:

$$AVC = \$92.97\, e^{(2.498+0.00051\,D^2)}$$

and by algebraic manipulation, the atomistic marginal cost function for the aircraft that are in the queue at the same time as the marginal aircraft is:

$$MC = \$92.97\, e^{(2.498+0.00051\,D^2)}[1 + 0.00102D^2].$$

To calculate the delays to aircraft that have yet to leave the gate, information is necessary on the nature of congestion over the course of the day. Figure 3 shows the queue length by time of day. In the morning there are periods of congestion because aircraft all seem to wish to depart at the same time at about the top of each hour. The queue then dissipates by about half past the hour. When no new aircraft join the queue until the congestion has dissipated, there will be no lingering effects on later departing aircraft as the airport has time to recover before the next bank of flights departs. In this case the MC_1 and MC_2 curves are one and the same.

Table 1 shows calculated congestion fees for different queue lengths in these circumstances. Following Brueckner, the congestion fees will vary by airline depending on the expected number of its own planes, and those of its regional affiliates, in the queue behind the marginal aircraft. Four types of airlines are shown. The first is a purely atomistic airline that has infrequent flights. An example at O'Hare would be Alaska Airlines that has just three flights a day. The second are airlines such as Northwest Airlines, Delta Air Lines or Continental Airlines which each have about 2.3% of flights. The final two are the dominant carriers, United Airlines with 40.5% of flights and American Airlines that has 48.8% of flights. The congestion fees vary from a modest $15-$30 when the queue lengths are very short, up to $800 for the dominant airlines and $1,600 for an atomistic airline at the busiest times in the morning when about 30 aircraft are in the queue. The calculations implicitly assume that fares are in equilibrium, and hence the airline internalizes the time costs of its passengers.

To put these figures in perspective, the landing fee for regular users of the airport in September 2004 was $2.591 per 1,000 pounds of landing weight regardless of carrier and time of day (City of Chicago, 2004). A Boeing 757-200 would currently pay $520, and a Canadair CRJ200 regional jet would pay $120. Moreover, these fees cover both the landing and the subsequent take off. In a system of congestion prices, an aircraft would be charged separately for landing and taking off.

In contrast to the morning, Figure 3 shows that the airport does not have recovery periods in the late afternoon and early evening (by this we mean that demand never falls back to the point where the demand curve intersects the AVC curve on its flat portion). The size of the total delay imposed by a marginal aircraft on later departures will depend on how the congestion prices change the pattern of traffic across the day. Based on the comparison of pricing in the morning with current landing fees, one would expect some flights would be priced out of the market and others would relocate to less busy times of day. One might expect that congestion pricing would flatten out the profile in Figure 3.

As a starting point to the analysis, congestion fees were calculated assuming that traffic patterns remain the same as today. The congestion fee will depend on when during the afternoon a flight is scheduled. Table 2 shows the congestion fee for flights that leave the gate at the top of each hour between 3pm and 8pm. The congestion fee is composed of two elements. The first is the delay caused to other aircraft that are in the queue behind the aircraft at the point it takes off. Estimation of this part of the congestion fee is obtained from the relevant line in Table 1. (The flight in question may have experienced a longer or shorter queue at the point it pushed back, but the congestion delays are only imposed on aircraft that follow it in the departure queue, not those that preceded it.) The second is the extra delay caused to each flight that subsequently joins the queue until the congestion clears at 8:45pm. Each of the departures in the second category faces a delay equivalent to the queue being one aircraft longer than it would have been had the marginal flight not been operated.

For a 3pm departure, the dominant airline would pay $8,700 and the atomistic airline would pay $17,000. By 6pm the fees are lower, at $4,500 and $8,800 respectively, because there are fewer departures remaining prior to congestion dissipating. By 8pm, the fees are approaching those that are charged in the morning hours.

As illustrated in Figure 1, the extremely high fees would undoubtedly make airlines consolidate flights or shift flights to less busy times of day. Therefore, in practical terms, one would expect that in setting prices there would be a period of disequilibrium as airlines adjusted their schedules. Even a relatively small change in the number of flights has the effect of reducing delays considerably. For example, we have simulated what would happen if 10% of the flights between 2:45pm and 4:45pm, a total of 15 flights, and 10% of the flights between 7:30pm and 8pm, a total of five flights, were discontinued or shifted to another time of day. Based on the assumption of the current maximum departure rate and a constraint of a minimum taxi-out time of eight minutes, the pattern of queue lengths in the late afternoon and early evening changes to that shown by the dashed line in Figure 3. Now the queue profile looks a lot more like that in the mornings, and the airport does have some recovery time at about half past each hour. The congestion fees will fall considerably as departure queues are shorter and aircraft are only charged for the delay caused to subsequent departures up until the point at which the next recovery period occurs, rather than for all departures until 8:45pm as is currently the case. The fee schedule in the early evening will be closer to that shown in Table 1.

7. Congestion Fees for Arrivals

Congestion also occurs for arriving aircraft. However, it is difficult to estimate the magnitude of the congestion fee for arrivals from the data set used in this analysis. The federal database only provides data on the time the aircraft lands ("wheels on") and the time the aircraft arrives at the gate. While taxi-in time is surely related to congestion on the ground, the majority of the congestion-related delays occur as aircraft are placed in a holding pattern waiting to land, are asked to slow down during the flight, or have ground holds at the originating airport. Data on these delays are not directly calculable from the Bureau of Transportation Statistics on-time data. While anecdotal evidence is that arrival congestion is less severe at O'Hare because arrivals tend not to be as peaked or bunched together as are departures, we would nevertheless expect arrivals to face fees of a similar magnitude to those charged for departures.

8. Comparison with Current Pricing

Congestion fees will have the characteristics that: (1) aircraft would be charged once for landing and again for taking off; (2) fees would vary by time of day and day of week and would depend on the number of aircraft desiring to take off or land at that moment and the number of subsequent aircraft movements until the congested conditions dissipate; (3) the fee would vary with market shares; and (4) fees would not, in general, vary by aircraft size, except to the extent that a particular type of aircraft would occupy the runway for a shorter or longer period than another type of aircraft, or requires additional spacing behind it due to wake turbulence. All of these run counter to the current weight-based price schedule, which is invariant with congestion and market share.

The congestion pricing scheme would result in fees that are lower than current landing fees at some times of day, but in general the fees would be higher, and in peak times considerably higher. For example, a $6,000 fee for an atomistic carrier would translate to a cost of $50 for each of the passengers on a 120-seat Boeing 737-700. In the new regime, these passengers would also be subject to fees for arrival at their destination, if that airport is also congested. However, in many cases the fees would be more modest. A departure on a 200-seat United Airlines Boeing 757 that is assessed a fee of $1,500 translates to just $7.50 per passenger.

The effect on ticket prices will depend on whether any net revenue gains from replacing landing fees with congestion fees are used to reduce or eliminate other charges and taxes currently imposed on airlines and their passengers. There are a wide variety of these charges. Departing passengers at the domestic terminals are assessed a passenger facility charge of $4.50 as part of their ticket price, and a larger amount is collected from arriving and departing passengers at the international terminal. In addition, there are federal taxes collected on all tickets in the form of a value-added tax of 7.5% on the base fare and a fee of $3.10 (in 2004) per segment to fund the operations of the Federal Aviation Administration and the Airport Improvement Program. Following the September 11, 2001 terrorist attacks, a Federal Security Service Fee of $2.50 per segment is also assessed. Airlines also pay a federal tax of 4.3¢ per gallon on jet fuel (Karlsson et al., 2004). Lastly, O'Hare charges airlines rent for the space they use in the terminals.

Of course, the primary explanation for the very high estimated congestion fees is that the rising demand for air services has overwhelmed the physical capacity of O'Hare. This is manifested in the expansion proposed by the O'Hare modernization plan. The standard highway congestion model recognizes that when capacity is constrained, excess revenues generated by the congestion fees can be used to fund expansion of the facility. Consequently, it would be appropriate that O'Hare should use a portion of any net revenue gain to funding the modernization plan, rather than having to rely on government grants and the issuance of bonds. By using the congestion fees to fund the modernization plan and to reduce or eliminate other fees and taxes, it is realistic to believe that congestion pricing can be implemented in a revenue-neutral way.

9. The Effect of Bad Weather

Delays at O'Hare become much worse when southwest winds require the use of a less-efficient configuration of runways. This was the case on Wednesday, September 15, 2004. During the morning southerly winds averaged 10 to 15 knots with gusts into the low 20s. At 3pm, concurrent with the start of the peak period, the winds shifted to the southwest and it started to rain.

Figure 4 shows a scatter plot of the observed taxi-out times plotted against queue length for the 990 domestic departures on that day. (A further 31 departures were canceled.) The maximum queue length of 67 aircraft at 7:15pm was more than 60% longer than on the good weather day. Maximum taxi-out times were almost twice as long as on the good weather day, and in some cases exceeded two hours. Flights with long taxi-out times had a variety of destinations suggesting that the long delays were not associated with ground holds due to poor weather at specific destination airports. While the delays were extensive, it is worth noting that the weather was not particularly severe. At no point were operations halted as they might have to be during heavy snow or thunderstorms.

A regression line fitted to the data in Figure 4 takes the form:

$$\ln(T) = \underset{(122)}{2.907} + \underset{(27)}{0.00027}\, D^2 + \varepsilon \qquad \text{Number of Observations} = 990, \quad \text{Adjusted } R^2 = 0.2779$$

with t statistics in parentheses. Predicted taxi-out times are longer on the bad weather day than the good weather day, even at low levels of queue length. For example, with a queue length of five aircraft, predicted taxi-out times are 12 minutes on the good weather day and 18 minutes on the bad weather day. Estimated functions for both the good and bad weather days predict a similar taxi-out time of 28 minutes when there are 40 aircraft in the queue, which is the maximum experienced on the good-weather day. At longer queue lengths, the function estimated on the bad-weather day predicts that taxi-out time would not rise as rapidly as would be predicted by extrapolating the function estimated on the good-weather day. Albeit, the predicted taxi-out time on the bad-weather day is 60 minutes when the queue reaches its maximum observed length of 67 aircraft.

The estimated relationship between queue length and taxi-out time can be used to calculate congestion fees for the afternoon and evening of the bad-weather day. The fees are much higher than on the good-weather-day because aircraft are delayed longer, and more flights are affected as the backlog of flights meant that congested conditions persisted until 11:30pm, compared with 8:45pm on the good weather day. As shown in Table 3, the congestion fee for a 3pm departure would be $660,000 for the dominant airline and a staggering $1.3 million for an atomistic airline, assuming current traffic levels.

This raises the question of whether a congestion price schedule should be based solely on the recurrent congestion experienced on a good-weather day or whether it should be based on some weighted average of the actual operations witnessed at the airport over the course of a year. Unfortunately the conditions experienced on September 15 are not that unusual. Not only is the airport configuration vulnerable to strong southwesterly winds, but this is also the prevailing wind direction in Chicago in the summer and autumn months. It is not surprising that the runway reconfiguration proposed in the modernization plan is aimed directly at improving traffic flow on days such as September 15.

10. Concluding Comments

Economists have long argued for pricing to ameliorate congestion problems in all modes of transportation. Market forces may have more success than recent brokered deals in shifting some flights out of the late afternoon and early evening hours. It would only require the shifting of relatively few flights away from the 3pm to 5pm and 7:30pm to 8pm periods to improve airport operations considerably.

Congestion prices may also lead to more minor flight rescheduling that will smooth out the spike in departures, and the consequent delays, that occur at the top of each hour. Currently, 37% of flights on the good weather day pushed back from the gate in the 15-minute period between ten minutes to the hour and five minutes after the hour. In contrast only 19% push back in the 15-minute period between 25 minutes after the hour and 20 minutes to the hour. In April 2002, American Airlines attempted to "de-peak" its hub-and-spoke structure at O'Hare by spreading out its operations across the hour (Zhang et al., 2004). Clearly this has not been effective in spreading out the queue, given that American operates almost 50% of the flights. One should note that congestion pricing does not necessarily lead to reduced hubbing. It would simply give airlines incentives not to operate the banks of flights at exactly the same time as other airlines that have a hub at the same airport and to move them to times other than the extremely popular top of the hour.

In the longer term, the congestion fees could provide revenue to fund the O'Hare modernization plan and galvanize support for the plan because the plan would reduce congestion, especially in poor weather conditions, and lead to fewer delays and an ultimate lowering of the landing and take-off fees.

Acknowledgments

The authors would like to thank the editor and two anonymous referees for comments that have improved this paper.

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Table 1: Estimated Congestion Fees When No Additional Aircraft Join the Queue until the Congestion has Dissipated

Queue Length at time of take off	Alaska Airlines	Delta Northwest Continental	United Airlines	American Airlines
	Atomistic	each 2.3% market share	40.5% market share	48.8% market share
5	$29	$28	$17	$15
10	$121	$118	$72	$62
20	$563	$550	$335	$288
30	$1,632	$1,594	$970	$835
40	$4,140	$4,043	$2,462	$2,117

Table 2: Current-Traffic Congestion Fees in Good Weather

Gate Departure Time	Wheels Off Time	Queue Length at time of take off	Alaska Airlines	Delta Northwest Continental	United Airlines	American Airlines
			Atomistic	each 2.3% market share	40.5% market share	48.8% market share
15:00	15:19	28	$16,878	$16,482	$10,035	$8,629
16:00	16:23	27	$12,848	$12,546	$7,638	$6,569
17:00	17:19	12	$9,958	$9,724	$5,920	$5,091
18:00	18:19	27	$8,688	$8,484	$5,165	$4,442
19:00	19:19	12	$5,241	$5,118	$3,116	$2,680
20:00	20:28	20	$670	$655	$399	$343

Table 3: Current-Traffic Congestion Fees in Bad Weather

Gate Departure Time	Wheels Off Time	Queue Length at time of take off	Alaska Airlines	Delta Northwest Continental	United Airlines	American Airlines
			Atomistic	each 2.3% market share	40.5% market share	48.8% market share
15:00	15:23	28	$1,295,448	$1,264,997	$770,164	$662,315
16:00	16:25	52	$1,211,078	$1,182,610	$720,004	$619,180
17:00	17:48	53	$970,900	$948,078	$577,215	$496,386
18:00	18:41	58	$688,229	$672,052	$409,163	$351,867
19:00	19:48	58	$256,887	$250,848	$152,723	$131,337
20:00	20:57	33	$26,653	$26,027	$15,846	$13,627

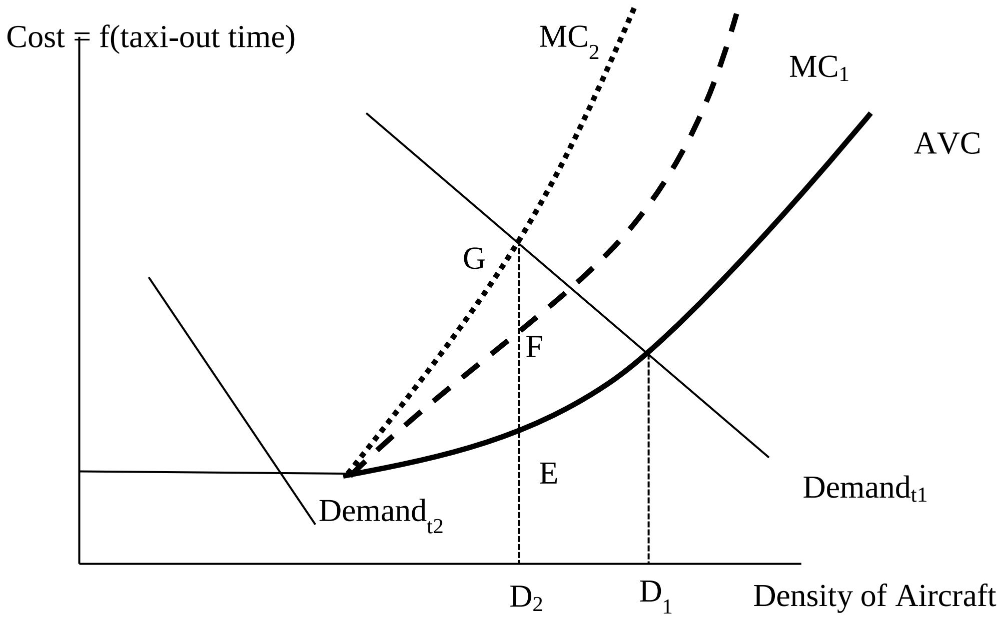

Figure 1: Standard steady-state congestion model

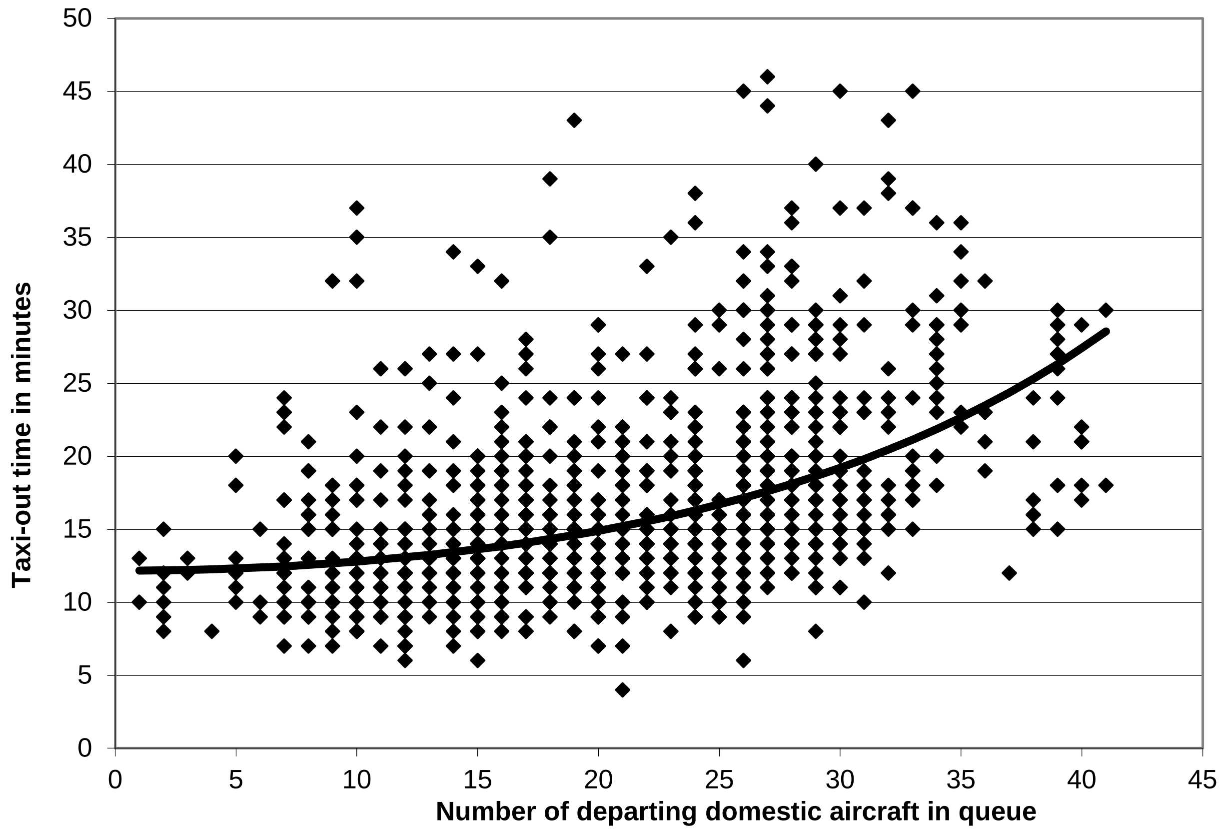

Figure 2: Actual versus predicted taxi-out times for September 22, 2004

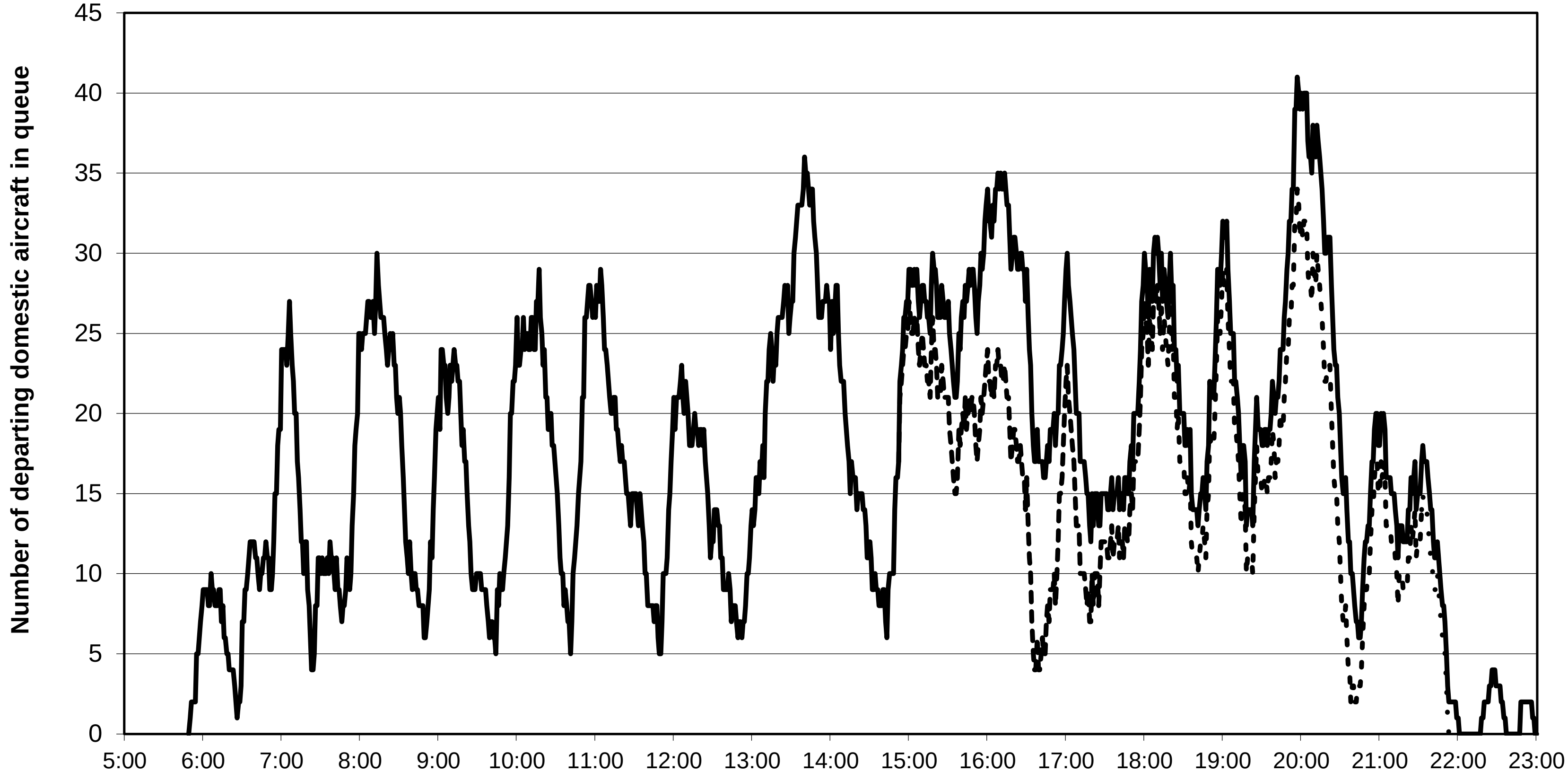

Figure 3: Queue length by time of day on September 22, 2004, with the effect of a 10% flight reduction between 14:45 and 16:45 and 19:30-20:00 shown as the dashed line

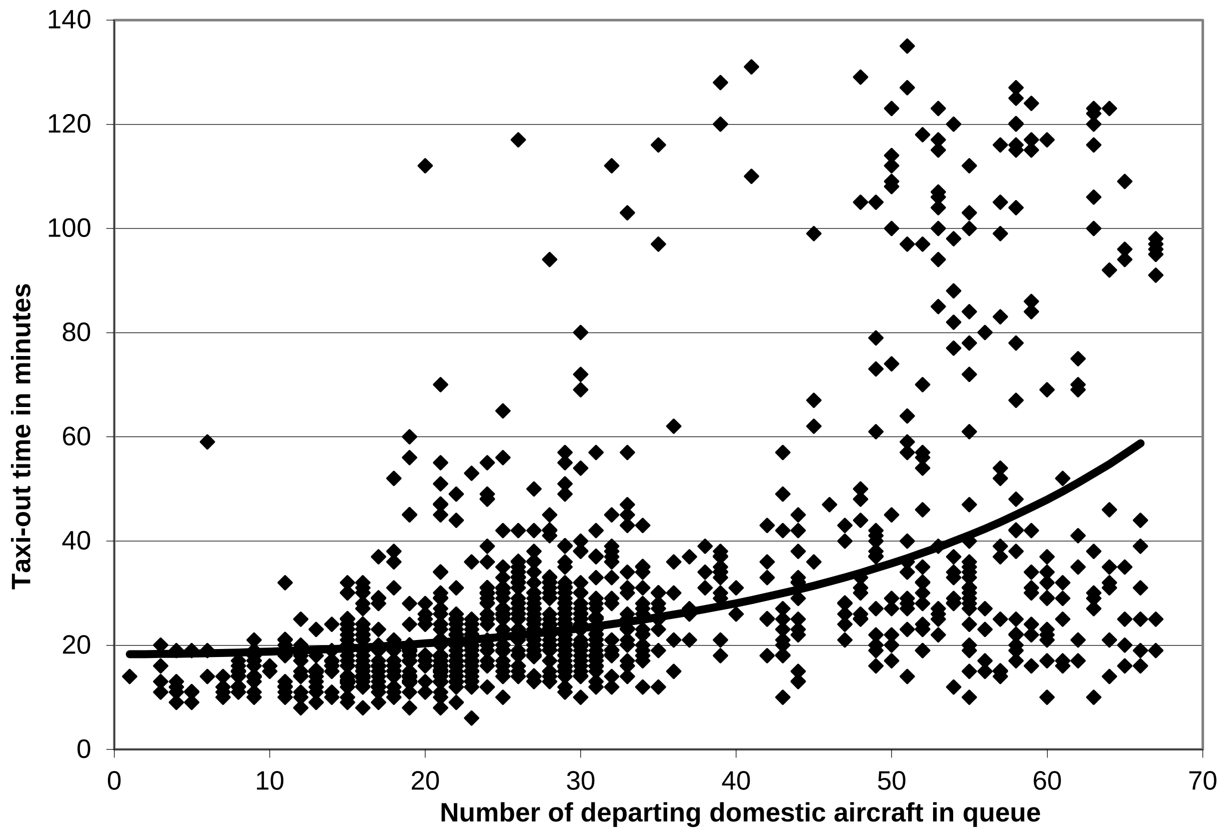

Figure 4: Actual versus predicted taxi-out times for September 15, 2004