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Determinants of Delays at European Airports

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Determinants of Delays at European Airports

ABSTRACT

Using flight data for the period 2000-2004 we find that four significant variables in explaining delays at European airports are market concentration, slot coordination, hub airports and hub airlines. We find evidence for the hypothesis that airlines internalize the effects of self-imposed congestion, but the results for the hub variables are somewhat puzzling. While delays are higher at hub airports, hub airlines experience lower delays than non-hub airlines. This may be at least partly explained by the special characteristics of the hub-and-spoke system in Europe, which is less extensive and more constrained, relative to the U.S. If introduced in Europe, efficient airport congestion tolls should be carrier-specific to account for the differences in internalization of delays.

KEY WORDS

Airport delays. Airport congestion. Hub-and-spoke. Congestion externalities. Airport demand management.

1. INTRODUCTION

Delays at airports have become a very common problem worldwide. In Europe, the Association of European Airlines (AEA) monitors delays at a number of selected major European airports[1]. In 2005 over 20 per cent of all intra-European flights leaving from these airports departed more than 15 minutes later than their scheduled departure time (AEA, 2006). In the U.S. the Department of Transportation's Bureau of Transport Statistics reports that 30 per cent of domestic flights arrived more than 15 minutes late in July 2007, up from 20 per cent in July 2003 (Carlton *et al*, 2007, p.4). These are just two examples of the magnitude of the flight delay problem.

Mayer and Sinai (2003) estimate a model relating congestion to hub-and-spoke operations and airport concentration. Hubs matter because interchange of passengers requires tight spacing of arrival and departure banks, causing congestion. Airport concentration matters because of internalization of congestion, as identified by Daniel (1995) and Brueckner (2002a,b). In Mayer and Sinai (2003) airlines are presumed to internalize the effects of self-imposed congestion, so that flights at an airport where one carrier operates most of the traffic will be scheduled to produce fewer delays than would result from the same flight volume at a less concentrated airport.

Using data on delays at the individual flight level, Mayer and Sinai (2003) confirm both the hubbing and internalization hypotheses by finding that flight delays are higher

[1] These are Amsterdam Schiphol, Athens, Barcelona, Brussels, Copenhagen, Dublin, Düsseldorf, Frankfurt, Geneva, Helsinki Vantaa, Istanbul Atatürk, Larnaca, Lisbon, London Gatwick, London Heathrow, Madrid Barajas, Manchester, Milan Linate, Milan Malpensa, Munich, Oslo, Paris Charles de Gaulle, Paris Orly, Roma Fiumicino, Stockholm Arlanda, Vienna, and Zurich.

at hubs and lower at concentrated airports. Brueckner (2002a,b) finds similar results using much more highly aggregated data. Extending Mayer and Sinai's methodology, Rupp (2009) finds hub effects but evidence against internalization, differentiating between delays from the airline's and passenger's perspectives. His measure of airline delay is excess travel time, defined as the difference between actual travel time and the minimum travel time on the route, while passenger delay is the difference between actual and scheduled arrival (and departure) times. Rupp finds that (a) from the airline's perspective, excess travel times tend to be lower at highly concentrated airports, indicating that airlines internalize airport congestion; and (b) from passengers' perspective, departure and arrival delays are more likely at highly concentrated airports, suggesting that airlines do not internalize passenger delay costs.

Rupp's conclusion against internalization matches evidence found in Daniel's (1995) paper and his subsequent work[2], which use a different methodological approach. When trying to determine the presence of atomistic behaviour, Daniel's work focuses on traffic peaks within a day. Mayer and Sinai (2003) and Brueckner (2002a,b), on the other hand, focus on differences in delays across airports, linking these delays to differences in market concentration in an indirect test for internalization.

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[2] Daniel and Harback (2008) do not find much evidence of internalization of delays by dominant airlines. They conduct specification tests using stochastic bottleneck models of airport congestion to determine whether dominant airlines internalize self-imposed delays at 27 major US airports for the period 28 July to 3 August 2003. The tests mostly reject internalization and fail to reject non-internalization by dominant airlines. They conclude that airport congestion charges should treat all delays as external.

The present paper achieves two goals: it extends Mayer and Sinai's methodology to the (unstudied) European case, and it provides further evidence on the disputed internalization hypothesis. The results on the internalization hypothesis are favorable, but the effect of hubbing on delays is less straightforward in Europe than in the U.S. context. Mayer and Sinai (2003) find that delays for a given airline rise both with overall airport traffic (measured by total destinations served) and with the size of the airline's own hub operation at the airport (again, measured by destinations). The current results confirm the first effect, but show that own-hub size has a negative rather than positive effect on delays.

Although the work reported here was initially inspired in Mayer and Sinai (2003), we soon found that the data that exist for Europe are not as rich or detailed as theirs. Most of the data used in this study were provided by the Central Office for Delay Analysis (CODA), which is part of Eurocontrol, the European Organization for the Safety of Air Navigation. There are three important data limitations. First, for confidentiality reasons, delay information on a flight-by-flight basis was not provided, and aggregates were provided instead. For this reason, it was not possible to replicate Mayer and Sinai's measure of excess travel time, defined as travel time not in excess of the scheduled time but in excess of the minimum feasible travel time (observed from individual flight data). Second, the time between landing and reaching the gate is not included in the data base provided by Eurocontrol, so that delay is computed as the difference between scheduled and actual landing time. Third, given that the measures of airline airport hub size are time invariant, airport fixed effects (dummy variables for each origin and destination airport, used by Mayer and Sinai (2003)) cannot be included when these variables are present. We can only include fixed effects if we do not include the airport hub size dummies.[3]

Section 2 discusses some important institutional features of European airports, which make them different from airports in other parts of the world, including the U.S. Section 3 presents the model and describes the data. Section 4 analyzes the main findings. Section 5 concludes.

2. THE EUROPEAN SETTING

In this section we briefly describe market concentration, hub-and-spoke patterns, and slot coordination in Europe, all of which present differences with respect to the U.S. case.

Airport market concentration, a key explanatory variable, is low in Europe, relative to the U.S. Concentration in the present paper is defined as the Herfindal-Hirschman Index (HHI) based on the share of flights by the various airlines that serve the airport. The HHI was computed for each airport in our sample and each season in every year (with the years being 2000 to 2004, and the seasons being winter, spring, summer and autumn).

The concentration at origin airports in our sample has a mean of 0.18 and a standard deviation of 0.12. This shows that European airports are in general not very concentrated, especially when compared to airports in the U.S. Mayer and Sinai (2003,

[3] The estimator given by an OLS regression is not defined if the specification simultaneously includes fixed effects for airports and variables which are constant throughout time for each airport.

p.1203, Table 1) report a mean concentration of 0.40 and a standard deviation of 0.21 for their origin airports.

Although, given the lack of origin-destination ticket data, it is difficult to tell for sure, the 'hub-and-spoke' system, so widely used in the U.S., does not seem to be as extensive in Europe. Burghouwt and Hakfoort (2001) and Brueckner and Pels (2007) give a number of possible reasons. These include shorter travel distances within Europe, where countries are small; competition from other transport modes, such as high speed rail; national interests standing in the way of the emergence of hubs in Europe;[4] and, airlines depending on bilateral agreements between their country and other countries for intercontinental services, despite deregulation of the European aviation market.[5]

In the U.S., four of the most congested airports, JFK and La Guardia in New York City, O'Hare in Chicago, and National Airport in Washington DC, are slot constrained. In Europe a far greater share of airports are slot controlled.[6] Member states in the EU are required to appoint an independent entity in charge of slot allocation at an airport, if

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[4] In contrast, the U.S. population lies within a single national boundary and there is no equivalent to a flag carrier system. The old flag-carrier regime in Europe also encouraged the emergence of point-to-point routes, with modest connecting traffic, and prevented the proliferation of efficient hub-and-spoke networks.

[5] These agreements may act as an obstacle in relocating a hub from one airport to another, for example.

[6] The list of slot constrained airports in Europe for the year 2004 is presented in the Appendix. Although the list was compiled for each scheduling period for each year between 2000 and 2004 and the information added on to the data base, there was little variation, with only a few airports changing the level of slot coordination during this period.

it experiences excess demand for usage. Thus, all airports in Europe can be classified as follows:

- Level 1: non-coordinated airports
- Level 2: schedule facilitated airports
- Level 3: fully coordinated airports

Non-coordinated airports are airports that have no excess demand, so that slot coordination is not needed. Schedule facilitated airports are airports 'where there is potential for congestion at some periods of the day, week or scheduling period' (IATA, 2005, p.7) and where schedules are facilitated by a coordinator, who seeks cooperation and voluntary schedule changes to avoid congestion. The slots are not actually allocated, and there is no preference according to historic use of slots (IATA, 2005, p.4). Fully coordinated airports are airports where the demand for facilities exceeds availability during the relevant period and where attempts to resolve problems through voluntary schedule changes have failed (IATA, 2005, p.11). All airlines wishing to land or take off at such airports during the periods for which they are fully coordinated need a slot allocated by a coordinator. Slot coordination is based on 'grandfather rights': a slot that has been operated by an airline entitles that airline to claim the same slot in the next equivalent scheduling period (winter or summer).

We highlight two points regarding slot coordination and the present study. The first point is that slot coordination is an important institutional feature at European airports, and the second point is that in the EU airlines do not schedule their flights freely but are restricted by the slots they are allocated (and therefore can use). Given the importance of slot coordination in Europe, it is used as an explanatory variable in our regressions.

3. DATA AND MODEL

Most of the data used in this study was provided by the Central Office for Delay Analysis (CODA), which is part of Eurocontrol, the European Organization for the Safety of Air Navigation.

The sample period was 2000-2004 and covered all domestic and intra-European flights. However, as mentioned above, delay information on a flight-by-flight basis was not available. Instead, the data set contained the sum of all delays for all flights operated by an airline from a given origin airport to a given destination airport for each season (winter, spring, summer and autumn) in each year (2000, 2001, 2002, 2003 and 2004). We then divided that sum of delays by the number of flights in order to obtain the average delay, which was the dependent variable in our model.

Data on the level of slot coordination (non-coordinated, schedules facilitated or fully coordinated) at each airport for each season and year was taken from the *Worldwide Scheduling Guidelines*, published periodically by IATA (2000a,b,c; 2001a,b; 2002a,b; 2004). The slot coordination levels do not vary much over time: once an airport is fully coordinated it is unlikely that it will become schedule facilitated or non-coordinated.[7][8]

In contrast with Mayer and Sinai (2003) and Rupp (2009), we find controlling for local airport demand difficult due to data limitations. They use Metropolitan Statistical Area annual data, whereas we use country annual data. Using country data for our

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[7] The only exception is Koeln/Bonn airport, which was fully coordinated and became schedule facilitated in winter 2001.

[8] 14 out of all 444 airports in Europe changed the level of coordination in the period under study. This is almost 10 per cent of the 141 slot constrained airports.

model, however, is not too problematic, given that competition among European airlines and airports tends to take place across countries, rather than within countries. Our demand variables include annual GDP per capita, population and unemployment rate for the countries where the origin and destination airports are located. These data were downloaded from the World Bank website. To address seasonal demand and weather fluctuations, all estimations include a season dummy (winter, spring, summer and autumn) along with year dummies.

Moving on to the model, in line with previous literature, and in particular with Mayer and Sinai (2003), we attempt to explain delays at European airports using the following variables:

CONCENTRATION, which refers to airport concentration and is measured by the Herfindal-Hirschman Index (HHI) at both the origin and destination airports during season *s* in year *t*. The intuitive sign for this coefficient is negative: the lower the concentration, the higher the expected delay. Airports with low concentration are characterized by many airlines with small market share.

SLOT COORDINATION LEVEL, determined at both origin and destination airports. Dummies for schedule facilitated and fully coordinated airports were used, and they measure effects relative to the non-coordination level. The expected sign for these coefficients is positive.

HUB AIRPORT, which is a collection of dummy variables capturing the airport's overall degree of hubbing, and *HUB AIRLINE*, which is a collection of dummy variables measuring airline's hub size at a given airport. Following Mayer and Sinai (2003) and Rupp (2009) we define *HUB AIRPORT* and/or *HUB AIRLINE* on the basis of an airport's connectivity. Thus, airports and airlines in Europe can be classified as follows:

- 0 to 14 destinations: non-hubs
- 15 to 44 destinations: small hubs
- 45 to 69 destinations: medium hubs
- 70 and more destinations: big hubs

The *HUB AIRPORT* and *HUB AIRLINE* variables indicate which category is relevant for a given airport, with the non-hub category being excluded.

At this point, it is important to understand that hub airline categories depend on the airline and the airport. In particular, an airline can be a hub airline at one airport (small, medium or big) and a non-hub airline at another airport. For example, Air France is a big hub airline at Paris-Charles De Gaulle but a non-hub airline at Madrid-Barajas, which is, however, a big hub airport for Iberia. The expected signs for included *HUB AIRPORT* and *HUB AIRLINE* dummies are in principle positive: the higher the number of connections relative to non-hub category, the higher the expected delay.

All specifications also contain a dummy for each airline, to control for characteristics unique to the airline that might influence delays, such as a high level of inefficiency. This dummy also accounts for the type of airline (charter, schedule, low-cost, cargo, etc).

The dependent variable in all our estimations is $DELAY_{ijkst}$. This is the average delay in minutes, computed as the difference between the actual landing-touch-down time and scheduled landing-touch-down time, for flights from origin airport *i* to destination airport *j* operated by airline *k* during season *s* in year *t*. Scheduled arrival time at the gate and actual arrival time at the gate would be more meaningful measures. Unfortunately, our data base does not include these measures, which is a shortcoming.

The average delay in minutes is calculated over <u>all</u> flights for a given route, for a given airline, for a given season and year.[9] A route is defined by an origin airport *i* and destination airport *j*, and route *ij* is different from route *ji*. As pointed out above, the clock starts at the time when the aircraft is scheduled to take-off and stops when it lands.

In contrast, the dependent variable in Mayer and Sinai (2003) measures excess travel time computed as time in excess of the minimum feasible travel time, equal to the 'shortest observed travel time' on a route (p.1201). We cannot construct such measure as we were not provided with travel times on a flight-by-flight basis. Mayer and Sinai's measure of delays offers the advantage of being independent from airlines' scheduling. Due to lack of data, we are not able to free our measure from these practices.

Our baseline delay model is therefore:

$$\begin{aligned} DELAY_{ijkst} = {} & \alpha + \beta_1 \text{CONCENTRATION}_{org,ist} + \beta_2 \text{CONCENTRATION}_{dest,jst} \\ & + \theta_1 (\text{SC LVL})_{org,i} + \theta_2 (\text{SC LVL})_{dest,j} \\ & + \gamma_1 (\text{HUB AIRPORT})_{\text{org},i} + \gamma_2 (\text{HUB AIRPORT})_{\text{dest},j} \\ & + \Psi_1 (\text{DEMAND})_{\text{org},ist} + \Psi_2 (\text{DEMAND})_{\text{dest},jst} + \delta_1 \text{YEAR}_t + \delta_2 \text{SEASON}_s \\ & + \delta_3 \text{AIRLINE}_k + \varepsilon_{ijkst} \end{aligned}$$

[9] Following international standards and definitions, a flight is considered on time if it arrives within 15 minutes of its scheduled arrival time. Therefore delays lower than 15 minutes are not included in the data base. If there are 100 flights on an *ij* route operated by airline *k* during season *s* in year *t*, and 90 are on time whereas 10 are delayed by more than 15 minutes, adding up to a total delay over the 10 flights of 180 minutes, the average delay, which is given by the dependent variable, $DELAY_{ijkst}$, is 1.8 minutes.

The extra subscripts *org* and *dest* are added to highlight that *i* and *j* represent origin and destination airports, respectively.

We then run two additional specifications, the first one adding the HUB AIRLINE dummies, and the second one including fixed effects. This second specification requires deletion of the *HUB AIRPORT* dummies, which show no variation over the sample period.

The summary statistics for the most relevant variables are presented in Table 1.

Table 1: Summary Statistics

Variable	Mean	Std. Dev.	Min.	Max.
$DELAY_{ijkst}$	10.89	12.11	0	518.67
Airline hub size				
15 - 44 destinations	0.02	0.15	0	1
45 - 69 destinations	0.02	0.14	0	1
70 + destinations	0.05	0.21	0	1
Airport hub size				
15 - 44 destinations	0.03	0.18	0	1
45 - 69 destinations	0.05	0.23	0	1
70 + destinations	0.18	0.39	0	1
Airport slot coordination level				
Schedule facilitated	0.18	0.38	0	1
Fully coordinated	0.53	0.50	0	1
Airport concentration				
	0.18	0.12	0	1

4. FINDINGS

4.1. Basic results

The results of the baseline specification are presented in Table 2. The regression was run for all airports and also for slot constrained airports only, which are busier and more congested. The sample including only slot constrained (SC) airports excludes all flights that where at least one endpoint was a non-coordinated airport.

All variables shown on Table 2 are significant at 1 per cent level. Flights originating from and arriving at airports with low concentration have higher delays, mirroring the results of Mayer and Sinai (2003) and Brueckner (2002a) and providing evidence of internalization of congestion. As expected, the positive *HUB AIRPORT* coefficients show that flights arriving at and departing from hub airports experience higher delays than those using non-hub airports.[10] Although the coefficients for the hubbing variables are similar between the full and SC samples, the concentration coefficients are larger in absolute value in the SC sample.

Interestingly, the results show that delays do not increase with the size of the hub: delays are lower for medium hubs than for small hubs and big hubs. A tentative explanation is that small hubs may be over-stretched in the use of their facilities during hubbing periods.

The slot coordination dummy has different effects for origin and destination airports, and for different samples. When all airports are included, delays at origin airports increase with the slot coordination level. In other words, delays are highest for fully

[10] The only coefficient with a counter-intuitive sign is the one for medium hub at destination. However its absolute value is very small.

coordinated airports, lower for schedule facilitated ones, and lowest for non-coordinated ones. For destination airports, the effect is difficult to interpret. When all airports are included in the sample, delays are lowest for schedule facilitated airports and highest for fully coordinated ones. It should be noted, however, that the absolute value of the negative coefficient is very small. When only slot coordinated airports are included in the sample, fully coordinated origin airports have higher delays than schedule facilitated ones, but for origin airports the coefficient, though positive, is very small.

The coefficients for the seasonal dummies show higher delays in spring and summer and lower delays in autumn, all relative to winter. Spring and summer may be seen as periods with higher demand and consequent congestion, which lead to even more delays than the bad weather conditions during the winter season. The coefficients for the demand variables have intuitive signs in all cases except for the unemployment rate at the origin airport.

Table 2: The effect of hub airport, slot coordination and airport concentration on flight delays in Europe, 2000-2004

Dependent variable: $DELAY_{ijkst}$*
Ordinary Least Squares

	All airports		**Slot constrained airports only**	
	Origin	Destination	Origin	Destination
Airport hub size				
15 - 44 destinations	1.45	1.30	1.17	1.83
	(0.007)	(0.007)	(0.009)	(0.009)
45 - 69 destinations	0.75	-0.16	0.88	0.01

	(0.007)	(0.007)	(0.009)	(0.009)
70 + destinations	1.39	3.61	1.81	3.86
	(0.004)	(0.004)	(0.005)	(0.005)
Airport slot coordination level				
Schedule facilitated	0.67	-0.098		
	(0.005)	(0.005)		
Fully coordinated	0.98	1.20	0.02	1.27
	(0.005)	(0.005)	(0.005)	(0.005)
Airport concentration	-3.23	-3.87	-7.16	-5.24
	(0.014)	(0.014)	(0.026)	(0.026)
Demand variables				
Annual GDP per capita	0.07	0.81	0.23	0.10
	(0.0025)	(0.0025)	(0.003)	(0.003)
Population	0.02	0.02	0.02	0.01
	(0.00008)	(0.00008)	(0.00009)	(0.00009)
Unemployment rate	-0.07	0.09	-0.05	0.15
	(0.0008)	(0.0008)	(0.001)	(0.001)
Seasonal variables				
Spring (Apr-Jun)	0.43		0.23	
	(0.004)		(0.005)	
Summer (Jul-Sept)	1.16		1.09	
	(0.004)		(0.005)	
Autumn (Oct-Dec)	-0.22		-0.31	
	(0.004)		(0.005)	
R^2	0.3146			
R^2 adjusted	0.3146			
F	11,593			
Number of observations	28,746,523			

$DELAY_{ijkst}$: average delay in minutes for flights from origin airport *i* to destination airport *j* operated by airline *k* during season *s* in year *t.*

The units used in the regression were \$10,000 for GDP per capita and millions for population.

Note: Standard errors are in parentheses. Equations also include dummy variables for year and airline.

4.2. Adding the HUB AIRLINE dummies

The second regression we ran was like the baseline one except that it also included the *HUB AIRLINE* dummies. The results are reported on Table 3. The regression was, again, run for all airports and for SC airports only. All variables shown on Table 3 are significant at the 1 per cent level. Like in Table 2, flights originating from and arriving at airports with low concentration have higher delays, which again, in line with Mayer and Sinai (2003) and Brueckner (2002a), can be taken as evidence of internalization. Once more, the absolute values of the coefficients for the concentration variable are higher for the SC sample.

As expected, flights arriving at and departing from hub airports experience higher delays than those arriving at and departing from non-hub airports. It should be noted that in this model, the coefficients for airport hub categories reflect not the (effect of hubbing on) delays experienced by all airlines at different airports when compared to non-hub airports, but rather the (effect of hubbing on) delays experienced by non-hub airlines at different hub size airports, when compared to those experienced at non-hub airports. Like in Table 2, delays are lower for medium hubs than for small hubs and big hubs. For the SC sample the pattern and coefficients are similar. The same explanation as before can be offered in this case: small and medium hubs experience similar levels of hubbing activities, with small hubs having more limited facilities in comparison to medium hubs.

The hub airline dummy coefficients show the estimated delays experienced by small, medium and big hub airlines when compared to delays experienced by non-hub airlines at the same hub size airport. Relative to non-hub airlines at hub airports, small, medium and big hub airlines have smaller delays, in both the all-airports and SC airports samples. In other words, an airline experiences lower average delays when it flies to or from its own hub. This finding is opposite to that in Mayer and Sinai (2003). They find that hub airports have higher delays and that hub airlines experience most of the delays at hub airports, pointing to the fact that hub airlines cluster their flights in "banks" of arrivals and departures as the reason. As logical as this explanation may sound, it is not verified in Europe. The reason is not quite clear but could be linked to one or all of the following explanations. First, the hub-and-spoke system in Europe is, as explained in Section 2, not as extensive in Europe as in the U.S., so that flight banking (and the attendant congestion) is not as pronounced. Second, given that the clustering of flights by hub airlines is constrained by slot coordination, it could be hypothesized that airlines are not completely free to schedule waves of arrivals and departures as they wish, with the constrained clustering leading to lower delays. Third, non-hub airlines in Europe are likely to hold fewer slots than hub airlines at their hubs. While hub airlines can swap flights between slots if they need to, non-hub airlines cannot, and so they experience higher delays. Finally, on-time arrivals for hub airlines are more valuable since they have connecting passengers whereas non-hub airlines likely do not.

The slot coordination dummy has coefficients similar to those from Table 2, except for the fully coordinated origin airports in the SC sample, where the coefficient is negative, albeit very small. The coefficients for the demand variables and seasonal dummies are virtually identical to those from Table 2, and the same interpretation also applies.

Table 3: The effect of hub airline, hub airport, slot coordination and airport concentration on flight delays in Europe, 2000-2004

Dependent variable: $DELAY_{ijkst}$*
Ordinary Least Squares

	All airports		Slot constrained airports only	
	Origin	Destination	Origin	Destination
Airline hub size				
15 - 44 destinations	-1.84	-2.18	-1.83	-2.02
	(0.009)	(0.009)	(0.012)	(0.118)
45 - 69 destinations	-2.00	-2.89	-1.86	-3.01
	(0.010)	(0.010)	(0.012)	(0.012)
70 + destinations	-1.42	-0.64	-1.62	-0.68
	(0.007)	(0.007)	(0.008)	(0.008)
Airport hub size				
15 - 44 destinations	2.13	2.16	1.86	2.61
	(0.008)	(0.008)	(0.010)	(0.010)
45 - 69 destinations	1.5	0.92	1.49	1.02
	(0.008)	(0.008)	(0.010)	(0.010)
70 + destinations	1.94	3.87	2.38	4.09
	(0.005)	(0.005)	(0.006)	(0.006)
Airport slot coordination level				
Schedule facilitated	0.69	-0.10		
	(0.005)	(0.005)		
Fully coordinated	0.94	1.15	-0.04	1.21
	(0.005)	(0.005)	(0.005)	(0.005)
Airport concentration	-3.03	-3.82	-6.54	-4.94
	(0.014)	(0.014)	(0.026)	(0.026)
Demand variables				
Annual GDP per capita	0.07	0.82	0.17	0.98
	(0.0025)	(0.0025)	(0.0034)	(0.0034)
Population	0.02	0.02	0.02	0.01
	(0.00008)	(0.00008)	(0.00009)	(0.00009)
Unemployment rate	-0.06	0.10	-0.04	0.15

	(0.0008)	(0.0008)	(0.001)	(0.001)
Seasonal variables				
Spring (Apr-Jun)	0.44		0.24	
	(0.004)		(0.005)	
Summer (Jul-Sept)	1.17		1.10	
	(0.004)		(0.005)	
Autumn (Oct-Dec)	-0.21		-0.30	
	(0.004)		(0.005)	
R^2	0.3186		0.2980	
R^2 adjusted	0.3185		0.2980	
F	11,746		9,117	
Number of observations	28,746,523		17,676,556	

$DELAY_{ijkst}$: average delay in minutes for flights from origin airport *i* to destination airport *j* operated by airline *k* during season *s* in year *t.*

The units used in the regression were $10,000 for GDP per capita and millions for population.

Note: Standard errors are in parentheses. Equations also include dummy variables for year and airline.

Before moving to the results of the last model, it is worth providing some quantitative evaluations of the effect of airport hub size and concentration on delays. The effect of airport hub size on delays follows a U-shape. For the all airports sample in Table 3, for example, the reduction in average delay when an airport is a medium hub rather than a small hub is 0.6 minutes for origin and 1.2 minutes for destination. The increase in delay when an airport is a big hub rather than a medium hub is 0.4 minutes and almost 3 minutes for origin and destination, respectively. For the SC airports sample, the signs are similar but the magnitudes larger in absolute value: reductions in average delay of 0.4 and 1.6 minutes when the airport is a medium rather than a small hub and increases in average delay of 0.9 and 3.1 minutes when the airport is a big rather than a medium hub, all for origin and destination respectively. When airport concentration increases by one standard deviation (i.e., 0.12, as shown in Table 1) the average delay decreases by roughly 0.4 and 0.5 minutes for origin and destination airports respectively.

4.3 Fixed effects model

Many specifications in Mayer and Sinai (2003), Mazzeo (2003) and Rupp (2009) include airport fixed effects, i.e. dummy variables for each origin and destination airport, in order to control for airport specificities, such as capacity and other factors, which can be difficult to measure directly. Table 4 presents the results of a specification which includes fixed effects. It should be noted, however, that in this specification the airport hub size dummy, which is constant throughout our sample period, is omitted to avoid perfect multicollinearity.

All variables shown on Table 4 are significant at the 1 per cent level. Although the signs of the airport concentration variable are still negative, just like in the baseline regression, their magnitudes in absolute value are higher, making a stronger case for internalization of delays. This result is different from that in Rupp (2009), who finds that airport concentration effects are considerably reduced after controlling for airport fixed effects. One important difference between Rupp (2009) and the present paper is that he is able to include the hub airport size dummy in his regression as well, and the estimated coefficients for this variable are also reduced when fixed effects are included.

The R^2's in Table 4 are the highest reported in the present paper, which indicates that the inclusion of time invariant airport effects plays an important role in explaining delays.

Finally, there is an important difference between this set of results and those in Tables 2 and 3 regarding the coefficients for the slot coordination dummy. For the sample that includes all airports, delays are lower at slot constrained airports (unlike in the previous regressions where, except for schedule facilitated destination airports, delays were higher) and go up with the level of coordination (i.e., they are higher at fully coordinated airports than at schedule facilitated ones). For the SC sample, delays are higher at fully coordinated airports than at schedule facilitated ones for both origin and destination airports, unlike the two previous regressions, where this result was only found for destination airports.

At first sight, the intuition behind these results could contradict our previous interpretation. Slot constrained airports are, by definition, busier and more congested, and therefore delays would be expected to be higher than at non slot constrained airports. On the other hand, it could be argued that slot coordination has the impact of reducing delays and this impact is only picked up when the hub airport dummy is excluded and the fixed effects are included. It is, however, difficult to offer a completely satisfactory explanation for the change in the sign of the coefficient for the slot coordination dummy.

Some of the coefficients for the demand variables have counterintuitive signs, but they are very small. The coefficients for the seasonal dummies are very similar to those reported on Tables 2 and 3 and the same interpretation applies.

Table 4: The effect of hub airline, slot coordination and airport concentration on flight delays in Europe, 2000-2004, including airport fixed effects

Dependent variable: *DELAY*$_{ijkst}$*
Ordinary Least Squares

	All airports		**Slot constrained airports only**	
	Origin	Destination	Origin	Destination
Airline hub size				
15 - 44 destinations	-1.64	-1.75	-1.83	-2.07
	(0.009)	(0.009)	(0.012)	(0.012)
45 - 69 destinations	-1.50	-1.65	-1.70	-1.97
	(0.010)	(0.011)	(0.013)	(0.013)
70 + destinations	-1.11	-0.40	-1.42	-0.60
	(0.007)	(0.007)	(0.008)	(0.008)
Airport slot coordination level				
Schedule facilitated	-2.17	-1.57		
	(0.020)	(0.020)		
Fully coordinated	-0.48	-1.19	1.98	1.37
	(0.020)	(0.020)	(0.020)	(0.020)
Airport concentration	-5.89	-4.89	-7.76	-6.47
	(0.029)	(0.029)	(0.047)	(0.047)
Demand variables				
Annual GDP per capita	0.31	0.02	0.12	-0.01
	(0.005)	(0.005)	(0.007)	(0.007)
Population	-0.65	-0.88	-0.63	-0.84
	(0.004)	(0.004)	(0.005)	(0.005)
Unemployment rate	-0.09	0.35	0.05	0.57
	(0.002)	(0.002)	(0.003)	(0.003)
Seasonal variables				
Spring (Apr-Jun)	0.37		0.22	
	(0.004)		(0.005)	
Summer (Jul-Sept)	1.07		1.08	
	(0.004)		(0.005)	

Autumn (Oct-Dec)	-0.22	-0.29
	(0.004)	(0.005)
R^2	0.3994	0.3818
R^2 adjusted	0.3993	0.3818
F	9,741	10,118
Number of observations	28,746,523	17,676,556

$DELAY_{ijkst}$: average delay in minutes for flights from origin airport *i* to destination airport *j* operated by airline *k* during season *s* in year *t.*

The units used in the regression were $10,000 for GDP per capita and millions for population.

Note: Standard errors are in parentheses. Equations also include dummy variables for year and airline.

5. CONCLUSIONS AND POLICY RECOMMENDATIONS

The purpose of this paper was to identify the causes behind delays at European airports. While there are a number of empirical studies on this matter conducted for the U.S. (such as for example, Mayer and Sinai, 2003 and Rupp, 2009), this is the first one ever done for Europe.

The variables we used were hub airport and hub airline dummies, airport concentration, slot coordination, and airline dummies. We also included demand variables as well as seasonal and year dummies.

While *HUB AIRPORT* coefficients indicate that delays at hubs are higher than at non hub airports, the effect does not increase monotonically with the size of the hub, but instead follows a U-shape. The hub airline dummies have puzzling negative coefficients, but this result may be explained by the facts that the hub-and-spoke system in Europe is not as extensive as in the U.S. and the waves of arrivals and departures are constrained by slot coordination at most hub airports. The coefficients for the airport concentration variable are negative, a finding that can be taken as evidence for internalization. Therefore, our results support the internalization hypothesis while offering a hubbing puzzle, which may be explained by the differences between European and American airports regarding hub-and-spoke operations and slot coordination.

Given our favorable results regarding internalization, we propose, like Brueckner (2002a,b) and Mayer and Sinai (2003), that a congestion charge should be set equal to the congestion externality not already internalized by the airlines. This toll would vary depending on the size of the airline, with large carriers (who internalize much of the congestion they create) paying a low toll and small airlines paying a high toll. Unfortunately, however, charging airline-specific tolls is probably not politically feasible. Morrison and Winston (2007), for example, argue that airlines would likely oppose a differentiated charging system. They argue that, in any case, the difference in welfare gains would be small because 'the bulk of airport delays are not internalized and because the efficiency loss from pricing internalized congestion is small' (p.1970).

REFERENCES

Association of European Airlines, 2006. *European Airline Punctuality in 2005*, February 23. http://www.aea.be/AEAWebsite/DataFiles/Pr06-007.pdf

Burghouwt, G., Hakfoort, J., 2001. The Evolution of the European Aviation Network, 1990-1998. *Journal of Air Transport Management* 7(5), 311-318.

Brueckner, J. 2002a. Airport Congestion When Carriers Have Market Power, *The American Economic Review* 92(5), 1357-1375.

Brueckner, J. 2002b. Internalization of Airport Congestion, *Journal of Air Transport Management* 8(3), 141-147.

Brueckner, J.K., Pels, E. 2007. Institutions, Regulation, and the Evolution of European Air Transport, in Lee, D. (Ed.), *The Economics of Airline Institutions, Operations and Marketing, Advances in Airline Economics*, Volume 2, Amsterdam/Oxford: Elsevier, Chapter 1, 1-26.

Brueckner, J.K., Van Dender, K. 2008. Atomistic congestion tolls at concentrated airports: seeking a unified view in the internalization debate, *Journal of Urban Economics* 64(2), 288-295.

Carlton, D., Heyer, K., Richard, O., Whalen, W.T. 2007. Proposal for a Market-Based Solution to Airport Delays, *Economic Analysis Group Discussion Paper*, EAG 07-14 October 2007. http://www.usdoj.gov/atr/public/eag/227380.pdf

Daniel, J. 1995. Congestion Pricing and Capacity of Large Hub Airports: A Bottleneck Model with Stochastic Queues *Econometrica*, 63(2). 327-70.

IATA 2000a. *Worldwide Scheduling Guidelines*, 1st Edition, International Air Transport Association, Montreal - Geneva.

IATA 2000b. *Worldwide Scheduling Guidelines*, 2nd Edition, International Air Transport Association, Montreal - Geneva.

IATA 2000c. *Worldwide Scheduling Guidelines,* 3rd Edition, International Air Transport Association, Montreal - Geneva.

IATA 2001a. *Worldwide Scheduling Guidelines,* 4th Edition, International Air Transport Association, Montreal - Geneva.

IATA 2001b. *Worldwide Scheduling Guidelines*, 5th Edition, International Air Transport Association, Montreal - Geneva.

IATA 2002a. *Worldwide Scheduling Guidelines,* 6th Edition, International Air Transport Association, Montreal - Geneva.

IATA 2002b. *Worldwide Scheduling Guidelines*, 7th Edition, International Air Transport Association, Montreal - Geneva.

IATA 2004. *Worldwide Scheduling Guidelines,* 10th Edition, International Air Transport Association, Montreal - Geneva.

IATA 2005. *Worldwide Scheduling Guidelines*, 12th Edition, International Air Transport Association, Montreal - Geneva.
http://www.iata.org/NR/ContentConnector/CS2000/SiteInterface/sites/whatwedo/scheduling/file/fdc/WSG-12thEd.pdf

Mayer, C., Sinai, T. 2003. Network Effects, Congestion Externalities, and Air Traffic Delays: Or Why Not All Delays Are Created Evil, *The American Economic Review* 93(4), 1194-1215.

Mazzeo, M.J. 2003. Competition and service quality in the U.S. airline industry, *Review of Industrial Organization* 22(4), 275-296.

Morrison, S., Winston, C. 2007. Another Look at Airport Congestion Pricing, *American Economic Review* 97(5), 1970-1977.

Rupp, N. 2009. Do carriers internalize congestion costs? Empirical evidence on the internalization, *Journal of Urban Economics* 65(1), 24-37.

APPENDIX: Slot constrained airports in Europe (for the year 2004)

Slot coordination level	Airport name	Country where airport is
Schedule facilitated	GRAZ	AUSTRIA
Schedule facilitated	INNSBRUCK	AUSTRIA
Schedule facilitated	KLAGENFURT	AUSTRIA
Schedule facilitated	LINZ	AUSTRIA
Schedule facilitated	SALZBURG	AUSTRIA
Fully coordinated	WIEN SCHWECHAT	AUSTRIA
Fully coordinated	BRUSSELS NATIONAL	BELGIUM
Schedule facilitated	SOFIA	BULGARIA
Schedule facilitated	LARNACA	CYPRUS
Fully coordinated	PRAHA RUZYNE	CZECH REPUBLIC
Fully coordinated	COPENHAGEN KASTRUP	DENMARK
Fully coordinated	HELSINKI-VANTAA	FINLAND
Schedule facilitated	BALE-MULHOUSE	FRANCE
Fully coordinated	LYON SATOLAS	FRANCE
Schedule facilitated	NICE	FRANCE
Fully coordinated	PARIS CH DE GAULLE	FRANCE
Fully coordinated	PARIS ORLY	FRANCE
Schedule facilitated	BREMEN	GERMANY
Schedule facilitated	DRESDEN	GERMANY
Fully coordinated	DUESSELDORF	GERMANY
Schedule facilitated	ERFURT	GERMANY
Fully coordinated	FRANKFURT MAIN	GERMANY
Schedule facilitated	HAMBURG	GERMANY
Schedule facilitated	HANNOVER LANGENHAGEN	GERMANY
Schedule facilitated	KOELN-BONN	GERMANY
Schedule facilitated	LEIPZIG/HALLE	GERMANY
Fully coordinated	MUENCHEN 2	GERMANY
Schedule facilitated	MUENSTER-OSNABRUECK	GERMANY

Schedule facilitated	NUERNBERG	GERMANY
Schedule facilitated	SAARBRUCKEN/ENSHEIM	GERMANY
Fully coordinated	SCHOENEFELD-BERLIN	GERMANY
Fully coordinated	STUTTGART	GERMANY
Fully coordinated	TEGEL-BERLIN	GERMANY
Fully coordinated	TEMPELHOF-BERLIN	GERMANY
Schedule facilitated	ATHINAI E. VENIZELOS	GREECE
Fully coordinated	CHIOS	GREECE
Fully coordinated	DIAGORAS	GREECE
Fully coordinated	IOANNIS/KAPODISTRIAS	GREECE
Fully coordinated	KARPATHOS	GREECE
Fully coordinated	KEFALLINIA	GREECE
Fully coordinated	KHANIA SOUDA	GREECE
Fully coordinated	KOS	GREECE
Fully coordinated	LIMNOS	GREECE
Fully coordinated	MAKEDONIA	GREECE
Fully coordinated	MEGAS/ALEXANDROS	GREECE
Fully coordinated	MIKONOS	GREECE
Fully coordinated	MITILINI	GREECE
Fully coordinated	NIKOS/KAZANTZAKIS	GREECE
Fully coordinated	PREVEZA/LEVKAS AKTIO	GREECE
Fully coordinated	SAMOS	GREECE
Fully coordinated	SANTORINI	GREECE
Fully coordinated	SKIATHOS	GREECE
Fully coordinated	ZAKINTHOS	GREECE
Schedule facilitated	FERIHEGY-BUDAPEST	HUNGARY
Fully coordinated	KEFLAVIK	ICELAND
Fully coordinated	DUBLIN	IRELAND
Fully coordinated	BERGAMO/ORIO ALSERIO	ITALY
Schedule facilitated	BOLOGNA	ITALY
Fully coordinated	CAGLIARI ELMAS	ITALY
Fully coordinated	CATANIA FONTANAROSSA	ITALY
Fully coordinated	FIRENZE/PERETOLA	ITALY

Fully coordinated	LAMPEDUSA	ITALY
Fully coordinated	MILANO LINATE	ITALY
Fully coordinated	MILANO MALPENSA	ITALY
Fully coordinated	NAPOLI CAPODICHINO	ITALY
Fully coordinated	PALERMO PUNTA RAISI	ITALY
Fully coordinated	PANTELLERIA	ITALY
Schedule facilitated	PISA SAN GIUSTO	ITALY
Fully coordinated	ROMA CIAMPINO	ITALY
Fully coordinated	ROME FIUMICINO	ITALY
Fully coordinated	TORINO/CASELLE	ITALY
Fully coordinated	VENEZIA TESSERA	ITALY
Schedule facilitated	LUXEMBOURG	LUXEMBOURG
Schedule facilitated	SKOPJE	MACEDONIA, EX-YUGOSLAV REPUBLIC OF
Schedule facilitated	MALTA LUQA	MALTA
Fully coordinated	EINDHOVEN	NETHERLANDS
Fully coordinated	ROTTERDAM	NETHERLANDS
Fully coordinated	SCHIPHOL AMSTERDAM	NETHERLANDS
Schedule facilitated	BERGEN/FLESLAND	NORWAY
Fully coordinated	OSLO/GARDERMOEN	NORWAY
Fully coordinated	STAVANGER/SOLA	NORWAY
Schedule facilitated	GDANSK/LECH WALESA	POLAND
Schedule facilitated	KATOWICE/PYRZOWICE	POLAND
Schedule facilitated	KRAKOW/BALICE	POLAND
Schedule facilitated	POZNAN/LAWICA	POLAND
Schedule facilitated	RZESZOW/JASIONKA	POLAND
Schedule facilitated	SZCZECIN/GOLENIOW	POLAND
Schedule facilitated	WARSZAWA/OKECIE	POLAND
Schedule facilitated	WROCLAW/STRACHOWICE	POLAND
Fully coordinated	FARO	PORTUGAL
Fully coordinated	FUNCHAL	PORTUGAL
Fully coordinated	LISBOA	PORTUGAL
Schedule facilitated	PONTA DELGADA	PORTUGAL
Fully coordinated	PORTO	PORTUGAL

Fully coordinated	PRISTINA	SERBIA AND MONTENEGRO
Fully coordinated	PRISTINA AIRPORT, UNMIK (ON A TEMPORARY BASIS)	SERBIA AND MONTENEGRO
Schedule facilitated	BRATISLAVA IVANKA	SLOVAKIA
Schedule facilitated	LJUBLJANA	SLOVENIA
Fully coordinated	ALICANTE	SPAIN
Fully coordinated	ALMERIA	SPAIN
Fully coordinated	BARCELONA	SPAIN
Fully coordinated	BILBAO	SPAIN
Fully coordinated	FUERTEVENTURA	SPAIN
Fully coordinated	GERONA	SPAIN
Fully coordinated	IBIZA	SPAIN
Schedule facilitated	LA CORUNA	SPAIN
Fully coordinated	LAS PALMAS	SPAIN
Fully coordinated	MADRID BARAJAS	SPAIN
Fully coordinated	MAHON/MENORCA	SPAIN
Fully coordinated	MALAGA	SPAIN
Fully coordinated	PALMA DE MALLORCA	SPAIN
Fully coordinated	REUS	SPAIN
Schedule facilitated	SANTIAGO	SPAIN
Fully coordinated	SEVILLA	SPAIN
Fully coordinated	TENERIFE NORTE	SPAIN
Fully coordinated	TENERIFE SUR	SPAIN
Fully coordinated	VALENCIA	SPAIN
Schedule facilitated	VITORIA	SPAIN
Schedule facilitated	ZARAGOZA	SPAIN
Schedule facilitated	GOTEBORG/LANDVETTER	SWEDEN
Fully coordinated	STOCKHOLM-ARLANDA	SWEDEN
Fully coordinated	STOCKHOLM-BROMMA	SWEDEN
Fully coordinated	GENEVE COINTRIN	SWITZERLAND
Fully coordinated	ZURICH	SWITZERLAND
Fully coordinated	ANKARA-ESENBOGA	TURKEY
Fully coordinated	ANTALYA	TURKEY
Fully coordinated	ISTANBUL-ATATURK	TURKEY

Fully coordinated	IZMIR-ADNAN-MENDERES	TURKEY
Schedule facilitated	MILAS/BODRUM	TURKEY
Schedule facilitated	MUGLA-DALAMAN	TURKEY
Fully coordinated	KIEV - BORISPOL	UKRAINE
Schedule facilitated	ABERDEEN	UNITED KINGDOM
Schedule facilitated	BIRMINGHAM	UNITED KINGDOM
Schedule facilitated	EDINBURGH	UNITED KINGDOM
Schedule facilitated	GLASGOW	UNITED KINGDOM
Schedule facilitated	LONDON/CITY	UNITED KINGDOM
Fully coordinated	LONDON/GATWICK	UNITED KINGDOM
Fully coordinated	LONDON/HEATHROW	UNITED KINGDOM
Fully coordinated	LONDON/STANSTED	UNITED KINGDOM
Fully coordinated	MANCHESTER	UNITED KINGDOM
Schedule facilitated	NEWCASTLE	UNITED KINGDOM

Source: *Worldwide Scheduling Guidelines* (IATA, 2004)