

# Optimal Air Traffic Delays

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**Abstract**— Airlines can control for excessive delays by introducing extra time in their schedule in addition to what is technically required. This is the so-called buffer time or buffer delay. We study the differences between unregulated markets - where airlines are free to fix buffer delays strategically - and a situation where a social planner would control for time schedules, and in particular buffer delays. To do so, we use a calibrated model of a network of three cities - one of them being a hub - served by a single airline. Welfare losses that follow from delays are relatively small as compared to the potential benefits that would follow from a decrease in ticket prices. The model thus advocates that, at least for the connections that are considered, prices rather than delays should be the focus of institutions aiming at enhancing passengers' welfare.

**Keywords**- Airlines; Delays; Social Optimum; Calibration

## I. INTRODUCTION

During the last decade, delays have become a common characteristic of European airports. About 42% of flights appear to be “delayed” between 2003 and 2009 in Europe. The evolution of delays over time is shaped by the economic crisis of 2008-2009 when the total number of flights changed from positive growth rates around 3.5% per year to a decrease of 6.6%. France presents higher figures mainly due to its central position in Europe.

The European Commission has been considering reforms aimed at harmonizing conflicting national rules and regulations as well as specific measures to protect passengers from the effect of delays. “Placing users at the heart of the transport policy” was one of the key actions proposed by the White Paper of the European Community Commission (2001). In the short term, the Commission intended to increase air passengers existing rights through new proposals concerning in particular, denied boarding due to overbooking, flight cancellations and delays.

The new regulation about passenger rights entered into force in February 2005 and increased compulsory monetary compensations in case of denied boarding to all kind of flights from and/or with destination in the EU. Although it included

only small compensations for “long delays”,<sup>1</sup> the Court of Justice of the EU ruled on 19<sup>th</sup> November 2009<sup>2</sup> that compensation may be payable as if the flight was cancelled where the resulting delay is longer than three hours.

It is plain that the policy proposed by the European Commission is very likely to be a superficial solution for the plague of delays. Carriers do not choose their schedule to have an average delay equal to zero. If penalties for air-traffic delays are significant, companies can simply respond by increasing their buffer delays, that is to say the extra-time introduced by companies in their schedule in addition to the minimum required travel time.

Buffer delays are a very widespread practice, in particular among airlines whose network is organized around a Hub<sup>3</sup>. In this case, buffer delay comes as a way to ensure that all passengers are able to get their connections. Note however that buffers may also turn out to be useful for companies that do not offer any connections i.e. low costs. Airlines use buffers to recover from delays by “padding” the schedule in order to improve the predictability of rotations and their punctuality performance with respect to published schedules. This practice not only reduces companies' operational costs but also the costs to passengers, that usually consider less painful to have a longer journey than to endure unexpected delays.

In Europe, according to Eurocontrol, 19.2% of flights departed before scheduled time and 39.7% of flights arrived before their scheduled time in 2009 compared to a 13% and 33% in 2005. The new regulation for passenger rights could have induced carriers to increase their scheduled travel time with respect to the average travel time. We want to study the

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<sup>1</sup> See European Commission (2005).

<sup>2</sup> Joined cases of *Sturgeon v Condor Flugdienst GmbH and Bock and others v Air France SA C-402 and 423/07*

<sup>3</sup> It is a common practice at US hubs to schedule longer flight times at the end of the day on a same market operated with the same airplane. Some airlines also introduce more buffer time on the morning to avoid concatenating delays all over the day. In France this practice is not allowed and airlines must choose a single scheduled time for all their flights on a given market operated with the same airplane.

optimality of their decision from a social point of view. It is plain that the socially optimum policy cannot consist in reducing to zero neither the difference between scheduled travel time and minimum travel time (the buffer delay), nor the difference between realized and scheduled travel time (the apparent delay). There is indeed a trade-off between travel-time decline (average efficiency) and delays reduction (schedules' reliability). Optimal delays (hence social costs of delays) depend upon market situation.

Characterizing the optimal policy and providing a guideline for its implementation would be a very difficult exercise. Instead, we assess first the potential benefits of such a policy through a simulation. The results of our calibration exercise suggest that, in the considered case, (i) Optimal buffer delays are *smaller* than actual buffer delays (*i.e.* travelers would prefer to have shorter journeys, even at a cost of more delays) and (ii) the welfare losses that follow from sub-optimal scheduling are relatively small as compared to the potential benefits that would follow from a decrease in ticket prices. However these results maybe highly determined by the characteristics of the particular network studied on the empirical section.

The paper is organized as follows. In section II, we review the few applied studies that reckon costs of delays and the theoretical literature on models of congestion and congestion charging. Section III introduces the main assumptions of the model. Section IV presents the firm's problem and outlines how demand parameters can be recovered. The maximization of social welfare is discussed in section V. In section VI, we describe the data for the market under scrutiny. Then using the calibrated demand parameters and these data, we apply the proposed methodology in section VII. Last section presents the conclusions.

## II. STUDIES ON COSTS OF DELAYS: FROM APPARENT DELAYS TO BUFFER DELAYS

Delays can be caused by several phenomena such as adverse meteorological conditions, strikes, accidents or congestion. Theoretical literature has focused on the later since around half of the observed delays occur due to congestion and congestion can be forecasted quite accurately. Congestion charging is broadly accepted as a key to achieve efficiency at congested airports and reduce overall delays. Several studies have been devoted to this subject, both theoretically and empirically e.g. Carlin and Park (1970), Park (1971) and Morrison *et al.* (1989). However congestion pricing presents several problems. First, as suggested by Schank (2005), it is hard to implement effectively. Second, given the lack of competitors at most of the European routes and the difficulty for new airlines to enter nearly all European Hubs, linking congestion fees and market power (*i.e.* charging more small operators) calls for undesirable effects that may well outweigh expected benefits.

Several authors study the relationship between congestion and market power of airlines. Typically an airline would not account for the congestion it imposes on competitors however airlines can anticipate congestion and adapt their behavior

accordingly. Thus, the higher its market share, the larger the proportion of the externality that is internalized. Brueckner (2003) show that congestion is fully internalized at airports dominated by a monopolist. Under a Cournot oligopoly, however, carriers are shown to internalize the sole congestion they face. These models explain why airports without a single dominant carrier could have high delays. However they do not explain the persistence of congestion at airports with a dominant large carrier. Moreover, Daniel (1995) rejects internalization of congestion at Minneapolis-St Paul airport. Brueckner (2002) exhibits some indications of negative correlation between congestion and airline concentration; however evidence is weak. Morrison and Winston (2007) did not find this negative association. Congestion (hence delays) cannot be explained by the sole failure of companies to internalize the externality they impose on others.

In Mayer and Sinai (2003), delays follow not only from congestion externalities but also from network benefits attached to the hub-and-spoke system. The authors consider delays as the difference between actual travel time and minimum travel time. Therefore they consider both apparent delays and buffer delays. According to their model, longer delays at hub airports are the efficient equilibrium outcome of a hub airline equating marginal (congestion) costs of an additional flight with its marginal (network) benefits. A single round-trip flight from (and to) a Hub connected with N airports generates indeed 2N different journeys.

The latter argument provides a rationale for observing congestion even in situations where there is no externality issue. However, the very fact that congestion may be profitable to firms does not say anything about its social desirability. The very idea of social gains coming from congestion is present in Betancor and Nombela (2002): although it may generate delays, an increase in frequency of services can increase the welfare of travelers. Nombela et al (2004) suggest that socially optimum buffer delay is likely to be strictly positive.

More generally, the assessment of the transportation system *cannot* spare an explicit reference to social optimum. Some congestion might be desirable, even from a social welfare point of view. Therefore, when attempting to estimate "social costs of delays", it does not make sense to consider the sole *observed* delays and give them a monetary value by coining a value of time. This was the traditional approach until now in the literature even if few studies have been yet devoted to the estimation of these costs. We highlight the research undertaken by Nombela et al. (2002) and the reports by the Institut du Transport Aérien (2000), and by the University of Westminster (2004). The estimated values for airlines and passengers costs depend heavily upon estimations of value of time from previous works and are relatively heterogeneous. Both ITA and University of Westminster consider observed and buffer delays for the cost estimation.

As pointed out in the latter, it is worth adding minutes of buffer delay to the airline schedule "up to the point at which the cost of doing this equals the expected cost of the [tactical]

delays they are designed to absorb". It is plain that when estimating the inefficiencies streaming from delays, one should not consider the difference between realized travel time and minimum travel time. For society, the real costs of delays stream from the difference between actual travel time and optimum travel time. The social cost of "delays" (observed and buffer) is therefore the loss in welfare that follows from the scheduling not to be "socially optimum" but decided by the firm. And the sole "delay" for which the firm can be unequivocally rebuked is the difference between the scheduled buffer delay and the optimal one. This is at least the approach adopted in this model and the view we advocate.

### III. THE MODEL: NOTATIONS AND DEFINITIONS

We consider a simple Hub-and-Spokes network (HS) in a model with stochastic delays. There are three cities labeled  $M_1$ ,  $M_2$  and  $M_3$ , and the flow of passengers between the cities  $M_i$  and  $M_j$  is denoted  $X_{ij}$ . The travel time between cities  $M_i$  and  $M_j$ , equals the minimum technical time required to flight between the two cities,  $T_{ij}$ , plus some stochastic delays  $\varepsilon_{ij}$  distributed according to the cumulative distribution  $\Phi_{ij}(\varepsilon)$ . Distributions of delays are considered to be (exogenously) given. In particular they do not depend upon (the pattern of) flows. In that sense, the model does *not* consider congestion issues. It rather focuses on the following issue: given the uncertainty attached to the (air) transportation system, how does socially optimal scheduling compare to the firms' profit-driven ones?

Airlines control this uncertainty introducing buffer time,  $\zeta_{ij}$  in other words, announcing longer travel journeys than the minimum travel time. The scheduled travel time is equal to the minimum required travel time,  $T_{ij}$ , plus the buffer time  $\zeta_{ij}$ . The cost to convey  $X_{ij}$  passengers from  $M_i$  to  $M_j$  is assumed to obey the following functional form:

$$C_{ij}(X_{ij}) = f + (\alpha + \beta X_{ij})T_{ij} + \xi_{ij}C_{\zeta}, \quad (1)$$

where  $T_j$  represents the minimum travel time between the cities,  $f$ ,  $\alpha$  and  $\beta$  are strictly positive parameter.  $C_{\zeta}$  is the cost linked to adding one minute of buffer time, which is expected to be smaller than the cost for a minute of observed delay. Obviously, the optimal network depends on the (expected) pattern of flows. A single company operates over this network. We assume that the HS network is an equilibrium outcome of our model. But we also assume that the resulting economies of density are high enough for this very same network to be socially optimal (On this, see Brueckner, J. K., and Zhang, Y. (2001)).

In the context of a Hub-and-Spoke network, some passengers have to take a connecting flight in order to reach their final destination. Under optimal conditions a passenger requires  $\underline{\delta}$  minutes to get his connection. Airlines could sell tickets with a connecting time equal to  $\underline{\delta}$ , however missing a connection represents a high cost for passengers. In order to decrease the probability of missing connections and equivalently to the buffer time introduced on direct flights, the company schedules later the connecting flights by introducing

a buffer delay  $\delta > 0$ . By doing so, however, the company increases the expected travel time of connecting passengers. There is thus a first trade-off between the costs and benefits of the (buffer) delay for connection,  $\delta$ . Observe that this trade-off regards connecting passengers only.

Because of the later, we know that  $\delta > 0$  so that the expected travel time will be larger than the minimum possible time (missing the plane is costly). We also know that  $\Phi_{ij}(\delta) < 1$ , meaning that the plane will arrive too late with positive probability. Thus, when the realization of the stochastic delay  $\varepsilon_{ij}$  exceeds the buffers delays  $\zeta_{ij} + \delta$  the airline may consider delaying departure of the second flight by  $\gamma$  (a real delay as opposed to  $\delta$  which consists in scheduling later the departure). This would benefit connecting passengers but would create a cost to all passengers of the departing flight.. Passenger with an arrival delay,  $\varepsilon$ , smaller than  $\zeta_{ij} + \delta + \gamma$  will not miss their connecting flight. Thus one can expect that  $\gamma \leq \delta$  (same marginal benefits from delay but higher marginal costs). Again since postponing the departure has a cost, we also know that  $\Phi_{ij}(\zeta_{ij} + \delta + \gamma) < 1$ . We also have  $\gamma > 0$  (missing the connection has a cost) so that, as result of delays of other flights' delays, passengers of direct flights will arrive late with positive probability. Note however that the later phenomena is conditional on the delay being "sufficiently large" (it must be larger than the buffers delays, i.e.  $\varepsilon_{ij} > (\zeta_{ij} + \delta)$ ), and yet, not "too large" (for the costs of delaying the flight not to overcome the benefits for the connecting passengers).

### IV. AIRLINE AND PASSENGERS PROBLEM

#### A. Airline Problem

We assume that a monopoly is serving the three city pairs. As we will explain in Section VI, the considered market for the calibration exercise is close to a monopoly situation. However, the lessons drawn from this model go much beyond this particular case as this situation is quite common within regional markets. In particular, despite the liberalization of the market, there is still a low level of competition on European markets as suggested by Billette de Villemeur (2004) or Neven et al (2006). Moreover, we observe that the optimal level of delays seems to be independent of the competitive structure of the market. In our model, the airline uses  $M_2$  as a Hub. The firm offers two direct flights between cities ( $M_1, M_2$ ) and ( $M_2, M_3$ ). It also offers indirect services from  $M_1$  to  $M_3$  through  $M_2$ . The stream of profits attached to direct flights is expressed by

$$P_{ij}X_{ij} - f - (\alpha + \beta X_{ij})T_{ij} - C_{\zeta}\zeta_{ij} - C_{\varepsilon}\varepsilon_{ij}. \quad (2)$$

where  $P_{ij}$  is the (one way) price for a seat on a flight that link the city pair ( $M_i, M_j$ ), and  $X_{ij}$  is the demand for that flight. Observe that, in addition to the (deterministic) operational costs already presented,  $f + (\alpha + \beta X_{ij})T_{ij}$  airlines face some costs due to arrival delays, both real  $C_{\varepsilon}\varepsilon_{ij}$ , and buffer  $C_{\zeta}\zeta_{ij}$ : We assume that demand takes a linear form:

$$X_{ij} = a_{ij} + b_{ij}(P_{ij} + vEt_{ij}). \quad (3)$$

where  $a_{ij} \geq 0$  and  $b_{ij} \geq 0$  are constants that are specific to the routes. By contrast, the constant  $v \geq 0$  is common to all routes. It denotes passengers' value of time while  $Et_{ij}$  comprises the scheduled time plus the average delay for route  $(M_i, M_j)$ .

There are three distinct markets, each associated to one city pair  $(M_i, M_j)$ . There are thus three demands,  $X_{12}$ ,  $X_{23}$  and  $X_{123}$  where the latest stands for journeys connecting  $M_1$  with  $M_3$  through the Hub  $M_2$ . Because  $(M_1, M_2)$  and  $(M_2, M_3)$  are distinct markets and passengers are offered a single alternative, their demand depend upon the sole characteristics of their journeys (price and expected travel time).

By assuming that consumers refer to the sole characteristics of the products they consume, we neglect substitution effects. Observe however that these same characteristics are still very much linked to each other. In particular, the expected travel time associated to each of the three possible journeys depends a-priori upon the whole flight schedule.

This is not the case however for passengers flying from  $M_1$  to  $M_2$ , the Hub. Since they enjoy a direct service, their expected travel time is equal to the scheduled travel time,  $T_{12} + \zeta_{12}$ , plus the average delay. Delays, as unexpected events, present higher costs for passengers than costs linked to scheduled travel time. De Palma and Rochat (1996), Noland and Polack (2002), and Bates et al. (2001) among others estimate the ratio between cost of scheduled time and cost of delays (late arrival). This ratio,  $r$ , is comprised between 1.03 and 2.69 according to their estimations. Therefore cost of delays is denoted by  $vr$ .

$$X_{12} = a_{12} + b_{12} \left( P_{12} + v \left( T_{12} + \zeta_{12} + r \int_{\zeta_{12} + \bar{\epsilon}}^{\infty} (\epsilon - \zeta_{12} - \bar{\epsilon}) \phi_{12}(\epsilon) d\epsilon \right) \right) \quad (4)$$

The literature has traditionally modeled costs of delays linearly even though passengers penalize more long delays than short delays. We consider the possibility that passengers do not punish companies for small delays introducing a non-linear approach. Passengers value the scheduled time spent travelling at a price  $v$ . If they suffer a delay but this is small, no cost is observed. On the contrary, when delays are superior to a significant threshold,  $\bar{\epsilon}$ , travelers suffer a cost,  $vr$ . We expect this cost to be higher than the cost linked to scheduled time,  $v$ , therefore  $vr > v$  and  $r > 1$ .

Passengers from  $M_2$  (the Hub) to  $M_3$  also benefit from a direct flight. However their expected travel time is subject to a higher uncertainty. If the realized delay attached to flights from  $M_1$  to  $M_2$  exceeds the buffer delay, that is if  $\epsilon_{12} > (\zeta_{12} + \delta)$ , the company can decide to introduce an extra delay in order for connecting passengers to get their correspondence. We are going to denote this extra delay by  $\gamma$ , the maximum time the airline will wait for its connecting passengers.

Therefore the expected travel time for passengers flying from the Hub is increased by the expected extra delay introduced by the airline. Their demand has the following form:

$$X_{23} = a_{23} + b_{23} \left( P_{23} + v \left( T_{23} + \zeta_{23} + rEd_{23} \right) \right) \quad (5)$$

$$Ed_{23} = \int_{\zeta_{12} + \delta}^{\zeta_{12} + \delta + \gamma} \int_{\zeta_{12} + \bar{\epsilon} + \zeta_{23} + \delta - \epsilon_{12}}^{\infty} (\epsilon_{12} - \zeta_{12} - \delta + \epsilon_{23} - \zeta_{23} - \bar{\epsilon}) \phi_{23}(\epsilon_{23}) \phi_{12}(\epsilon_{12}) d\epsilon_{23} d\epsilon_{12} \\ + \left( \int_0^{\zeta_{12} + \delta} \phi_{12}(\epsilon_{12}) d\epsilon_{12} + \int_{\zeta_{12} + \delta + \gamma}^{\infty} \phi_{12}(\epsilon_{12}) d\epsilon_{12} \right) \int_{\zeta_{23} + \bar{\epsilon}}^{\infty} (\epsilon_{23} - \zeta_{23} - \bar{\epsilon}) \phi_{23}(\epsilon_{23}) d\epsilon_{23}$$

Passengers flying from  $M_1$  to  $M_3$  through the Hub face the longest and most complex journey. Their travel time equals the minimum travel time required for the trip,  $T_{12} + \underline{\delta} + T_{23}$  plus the buffers,  $\zeta_{12} + \delta + \zeta_{23}$  if delays are smaller than the latter. If delays are comprised between  $\zeta_{12} + \delta$  and  $\zeta_{12} + \delta + \gamma$ , the airline introduces an extra delay,  $\gamma = \epsilon_{12} - \zeta_{12} - \delta$ , to ensure the connection. If delays are bigger than  $\zeta_{12} + \delta + \gamma$  passengers lose their connecting flight and will have to attend for the next one. This implies an extra waiting time that we denote  $Ewt$ . The airline gives compensation  $C_{lf}$  to each passenger losing its connection. In any of the 3 cases passengers can suffer a delay on their last flight to attain their destination.

Given these demands, the firm maximizes the expected total profit choosing prices, buffer delay, and maximum extra time that it can introduce to facilitate connection for passengers. Profit is a function of observed delays. If  $\epsilon_{12} < (\zeta_{12} + \delta)$ , connecting passengers catch their flights. The firm does not need to introduce extra delays and profits are at their maximum level,

$$\Pi(P_{ij}, \delta, \gamma, \zeta_{ij} | \epsilon_{12} < (\zeta_{12} + \delta)) = P_{123} X_{123} - \delta C_\delta - (\zeta_{12} + \zeta_{23}) C_\zeta + \\ P_{12} X_{12} - f - (\alpha + \beta(X_{12} + X_{123})) T_{12} - C_\epsilon \int_{\zeta_{12}}^{\infty} (\epsilon_{ij} - \zeta_{12}) \phi(\epsilon_{ij}) d\epsilon_{ij} + \\ P_{23} X_{23} - f - (\alpha + \beta(X_{23} + X_{123})) T_{23} - C_\epsilon \int_{\zeta_{23}}^{\infty} (\epsilon_{ij} - \zeta_{23}) \phi(\epsilon_{ij}) d\epsilon_{ij} \quad (6)$$

where  $C_\epsilon$  represents the cost per minute for the airline of suffering a delay.  $C_\delta$  represents an opportunity cost for the airline, i.e., the cost an airline supports choosing how long planes are stopped at airports and how much time they are flying. When an airline decides to increase buffer delay at the Hub, it reduces the number of plane's rotations; therefore the plane spends more time at airports than flying, and consequently costs per day decrease. If the airline reduces buffer delay, the plane has to wait less time at the Hub and is able to increase its rotations in a day so that total costs are increasing.

If  $\epsilon_{12} > (\zeta_{12} + \delta)$  the airline can introduce an extra delay at a cost per minute of  $C_\gamma$ , or make the passengers flying from  $M_1$  to  $M_3$  lose their connecting flight and pay a penalty  $C_{lf}$  per passenger due to the new regulation on delays. In the first case  $(\epsilon_{12} - \zeta_{12} - \delta) C_\gamma$  is subtracted to (6) and  $C_{lf} X_{123}$  in the second one. The firm maximizes total profit choosing  $P_{ij}$ ,  $\zeta_{ij}$ ,  $\delta$  and  $\gamma$ . At equilibrium, profit maximizing conditions together with demand equations must be satisfied. From this system of equations we can recover all unknown parameters.

## B. Passenger Problem

Passengers are assumed to maximize their net utility given by  $U_{ij} - P_j X_{ij} - cEt_{ij} X_{ij}$  where  $U_{ij}$  is the gross utility that consumers obtain from travelling. To maximize their net utility  $U'(X_{ij}) = P_j + cEt_{ij} = \tilde{P}_{ij}$  must be satisfied, where  $\tilde{P}_{ij}$  is the generalized price. Once we calibrate the parameters of demand, gross utility obtained by passengers,  $U_{ij}$ , can be recovered by integration of the generalized price,  $\tilde{P}_{ij}$ , over  $X_{ij}$ .

$$X_{ij} = a_{ij} + b_{ij} (P_j + cEt_{ij}) = a_{ij} + b_{ij} \tilde{P}_{ij} \Rightarrow \tilde{P}_{ij} = \frac{X_{ij} - a_{ij}}{b_{ij}} \quad (7)$$

$$U_{ij} = \int_0^{X_{ij}} U'(x) dx = \int_0^{X_{ij}} \tilde{P}(x) dx = \frac{(X_{ij})^2}{2b_{ij}} - \frac{a_{ij} X_{ij}}{b_{ij}}$$

## V. WELFARE

The report aims at evaluating the difference in social welfare between optimum and equilibrium. Welfare results from the addition of passengers' surplus for each flight minus the cost of producing the flights.

$$\text{Max}_{\delta, \gamma} [U_{12} + U_{23} + U_{123} - \text{Costs for passengers} + \text{Firm's Profits}] \quad (8)$$

Given that we aim at maximizing welfare two options are possible: maximize with respect to  $\delta$ ,  $\zeta_{ij}$  and  $\gamma$  or additionally do so with respect to prices. Two ideas are behind the former. First, the social planner cannot interfere in the companies' pricing decision or when it can, the social planner believes the firm works in a competitive environment and hence it will set a price approximately equal to the social marginal cost that is to say the solution under social welfare maximization. Instead we additionally maximize with respect to prices when the social planner believes the firm is not working under competition and the social planner can choose the prices.

We evaluate both possibilities, however, given that price intervention is not considered, the analysis sticks to the first case and we only present the results for the latter in section VII. Therefore we compute  $\delta^*$ ,  $\zeta_{ij}^*$  and  $\gamma^*$ , the buffer and extra delay that maximizes social welfare and obtain the social cost of delays as the difference between welfare evaluated at  $\zeta_{ij}^*$  and  $\gamma^*$  and the welfare at equilibrium.

## VI. DATA

Our model is validated in a network composed of the cities Toulouse, Paris and Nice where Paris operates as a Hub. Data are available for all flights in the network during May and June of 2004. Average data for frequencies of flights, passengers of each flight, capacity and schedule travel time are presented in Table 2 for each direct route of the main airline. There exists one competitor for the routes Toulouse-Paris and Paris-Nice, however the degree of competition is low since it only offers 4 daily flights in each route 23 and 20 flights offered by the main

**Table 1: Average data**

Direct Flights	Toulouse-Paris	Paris-Nice
Total passengers	177414	166831
Total n° of flights	1432	1228
Average Pax / flight	123.9	135.9
Travel time (minutes)	80	85
Frequencies <sup>a</sup>	23.5	20.1
Airplane <sup>b</sup>	A320	A320
Capacity <sup>c</sup>	161.9	168.1
Average occupation	76.5%	80.8%

<sup>a</sup> Average frequency of flights per day; <sup>b</sup> Most frequent plane; <sup>c</sup> Average capacity of the planes operated on the route.

airline) which transport 14.78 % and 16.3 % of daily passengers respectively. As shown in section VII, the level of competition on the observed market has small effects over the optimal level of delays. Tariffs are available for different kinds of consumers under different conditions, though the average price per passenger as well as the percentages of business and leisure travelers remains unknown. The chosen prices are 80 Euros for Toulouse-Paris, 95 Euros for Paris-Nice and 120 Euros for Toulouse-Nice via Paris. All prices are one-way.

No information is available about passengers travelling from Toulouse to Nice through Paris,  $X_{123}$ . On average 5 % of passengers arriving to Paris from Toulouse and Nice take another plane to get their final destination. We assume that connecting passengers on Paris-Nice represent also 5 % of the total number of passengers on this route.

Arrival delays in each route, are assumed to be distributed according to a gamma distribution. Its scale and shape parameters are estimated by maximum likelihood. Delays are stochastic and therefore the only tool for airlines to deal with them is buffer delay for the schedule and the extra delay at the tactical level.

Concerning extra delays introduced by the airline in its departure flights from Paris to Nice, we look at all observed departure delays. Extra delays included by the company to wait for connecting passengers represent 14.7% of the observed departure delays with an average of 0.81 minutes per flight.

The cost of adding an extra minute of delay,  $C_\gamma$ , is available from different studies. Nombela et al (2002) consider a cost for airline delays of 83 €/hour. The Westminster study presents a similar value, 72 €/hour of delay. In contrast values provided by ITA (2000) are comprised between 35.5 and 50.9 €/hour and IATA (1999) consider 37.5 €/hour. This difference is due to the inclusion in the first case of costs related to loss of market share to other airlines or to other modes and loss of corporate image. These costs are captured in our model by the very dependence of the passengers' demand on the expected travel time. Therefore we consider the range of values proposed by ITA (2000). As the airline generally operates the same airplane's model for both routes we assume that  $\beta$ ,  $C_\gamma$ , and  $C_\delta$  are the same in both routes

We consider low values for  $\beta$ , between 0.005 and 0.03, since it measures the variable cost per passenger per minute on a given flight. Finally,  $C_{lf}$  is the hard costs for the airline of a passenger losing its connection, that is to say compensations and rebooking. We are assuming that at the studied period these costs were zero. The waiting time for passenger losing its connection to take the next flight,  $Ewt$ , is computed from frequencies of flights serving the second part of the trip. Departures are not evenly distributed so that we observe small changes on this variable depending on the hour of the day. Given the small magnitude of these variations, there is no restriction on assuming that this additional waiting time is constant and equal to its average value, 40 minutes.

The expected waiting time for passengers at Paris is a stepwise function of the minimum time required for connection  $\underline{\delta}$  and appears to be constant over 15 minutes' intervals. On the one hand, Air France offers several flights with a connection time of 30 minutes for Paris-Orly in several route pairs combinations, included the ones studied in this case. Consequently, it seems to be fair to assume that the minimum required time for a connection  $\underline{\delta}$  is smaller than 30. On the other hand, it appears reasonable to consider it larger than 15. We assume a value equal to 20 minutes and test on the next section the effects of changes in this variable.

## VII. RESULTS

The results as well as the values proposed for the calibration are presented in Table 5. The absolute values of the price elasticities are 1.02 for Toulouse-Paris, 1.02 for Paris-Nice and 1.03 for Toulouse-Paris-Nice. As expected, given the monopoly assumption, they are larger than 1.

The cost of observed delays is in general higher than the cost of buffer delays. Even though the ratio  $r$  and the value of buffer time  $\nu$ , can vary significantly as a function of different parameters, their product, the cost of delays remains pretty stable with values comprised between 0.85 and 0.95 Euros per minute (51-57 Euros per hour).

This cost of delay, can be considered as high, especially when compared to the values proposed by Nombela et al (2002) (21€ per hour for business travelers and 15€ per hour for leisure travelers). Institut de Transport Aerien (2000) assigns a range comprised between 0.57 and 0.73 Euros per air passenger and minute (34-44€ per hour) closer to our values.

It is interesting to notice the role of non-linearities for cost of delays on the calibration. The ratio  $r$  increases with the threshold fixed for significant delays (obtaining always values superior to 1 from 5 minutes of delay). This sustains the hypothesis that cost of delays is not linear and increases with the size of delays.

We can calculate the buffer and extra delays that maximize the social welfare  $\delta^*$  and  $\gamma^*$ . We consider two different approaches. If the government maximizes social welfare taken into account the reaction of the firm on prices, welfare is maximized for  $\delta^* = 12.91$  minutes,  $\gamma^* = 0$ ,  $\zeta_{12} = 11.75$  and  $\zeta_{23} = 9.67$ . Whatever the changes applied to the parameters used on

**Table 2: Results from the calibrated demands**

Values proposed for the calibration				Results	
$P_{12}$	80	$X_{12}$	118.47	$a_{12}$	323,35
$P_{23}$	95	$X_{23}$	130.52	$b_{12}$	-1,50
$P_{123}$	120	$X_{123}$	5.34	$a_{23}$	346,60
$T_{12}$	55	$\zeta_{12}$	25	$b_{23}$	-1,39
$T_{23}$	64	$\zeta_{23}$	21	$a_{123}$	17,46
$\underline{\delta}$	20	$\delta$	25.04	$b_{123}$	-0,05
$\gamma$	0.81	$Ewt$	40	$\nu$	<b>0,69</b>
$C_\gamma$	40	$C_\epsilon$	40	$r$	<b>1,25</b>
$\beta$	0.02	$C_{lf}$	0	$C_\delta$	-3,19
$\bar{\epsilon}$	10			$C_\zeta$	-65,13

the study, at the optimal point, both parameters decrease. Passengers prefer to enjoy a smaller average travel time and face a bigger probability of losing their connecting planeor in general suffering a delay.

If these values are imposed to the airline the gain in welfare for the society is 517 Euros which represents an increase in 1.43% of welfare with respect to the equilibrium situation. Extra delays disappear at the optimal situation since the probability of losing a connection and the extra waiting time are low while the cost of introducing extra delays is considerably high for the company. Moreover few passengers would profit from them compared to the number of passengers for who it represents a cost. If these elements are attenuated we find optimal solutions where both buffer delay and extra delays are positive and larger than zero while they are always lower than the values at equilibrium

Under the optimal solution demand increases in the three considered routes even if prices increases in a similar percentage. For route Paris-Toulouse-Nice demand increases 7% while price increases 6.8%. Toulouse Paris increases 4.5% price increases 4.4% Paris nice+3 price +2.9%

It is difficult to compare our results with the ones obtained at previous studies since our analysis is focused on buffer delay and not "apparent delays", defined as the difference between the realized travel time and the scheduled one. The study by the University of Westminster proposes a value comprised between 0 and 16.3 Euros per buffer minute for airlines. However the study states that "these are fairly rudimentary estimates". Besides, it takes into account only the airline side while we consider the overall effects over airlines and passengers.

The study by ITA (2000) assumes that cost for passengers of buffer delay is equal to the cost for a delay which seems to be far from reality. It also assumes that airlines' cost for buffer delay is even slightly bigger than cost of delays, which makes unreasonable the existence of buffer delays. And finally Morrison and Winston estimates a cost of 0.08€ per minute for buffer delay in main US airports.

### C. Sensitivity analysis

For any of the chosen parameters two questions can arise: 1) What are the effects over the calibration of demand and over the optimal welfare of a measurement error in any of the parameters? 2) If our values are correct, what effect over welfare results from a change in any of the parameters? In both cases, effects are negligible for most of the parameters. For example, changes in the minimum time required for passengers to connect,  $\delta$ , or changes in the variable cost per passenger  $\beta$  have insignificant effects over the calibration of demand or the optimal social choice. Other variables require a more detailed analysis.

*Changes in Prices:* The cost of delays for passengers,  $\delta^*$ ,  $\gamma^*$  and the gain in welfare remains unaffected by any change in prices. In particular if price were 25% lower only parameters  $a_{ij}$  and  $b_{ij}$  are modified on each demand but no change is observed on cost of delays and optimal schedule choices. The price elasticity of demands increases if prices decrease, but slower rate. By contrast, if we look at effects over welfare of a 25% decrease in prices with the actual setting, welfare increases almost 13%. On the other hand, with a decrease higher than a 50% in buffer delays, the increase on welfare is of only 1.4% (the same effect can be obtained with a reduction in prices of 2.5%). Therefore, effects of changes in prices over welfare are of first order magnitude while changes of buffer delays produce a second order effect over welfare.

*Changes over welfare of introducing  $C_{ij}$ :* We assume that  $C_{ij} = 0$  at equilibrium. We study the effects of introducing compensations for passengers losing their connections given the low probability of suffering long delays on the studied markets. Any compensation leads to higher prices for connecting passengers and a decrease on welfare. Only very high compensations affect to the choice of buffer delays, increasing specially the minutes of buffer at the connecting airports. The airline can also decide to increase buffer time for the second segment of the flight (Paris-Nice) however in this case it has to compensate all the direct passengers with a price reduction. The effects remain small for small compensations however if we consider the highest possible compensation for delays for this particular route introduced by the European Commission, which is around 250€ welfare reduces 3.8%, more than doubling the possible gain from imposing optimal delays.

*Effects of changes over the number of connecting passengers:* *Ceteris paribus*, for a higher number of connecting passengers, we expect to find a smaller cost of delay and therefore a smaller gain in welfare. In fact, for a similar buffer delay and a higher number of connecting passengers (which implies that direct flight passengers have decreased), the probability of passengers losing connections rest unchanged while their weight over the market has increased. Therefore cost of delay is less important than in the case where connecting passengers are lower. Vice versa, if we believe that the number of connecting passengers was smaller than what we assumed, we would expect a bigger cost of delay.

Costs of delays estimations are sensible to changes in this variable, especially when we decrease it. By contrast the optimal buffer delay and extra delays remains almost unaltered. For example, if we decrease the number of connecting passengers 20%, we observe that the cost of delay increases to 1.09€/minute (an increase of 27%). Conversely when we increase this value, in the same proportion, 0.5%, the cost of delay decreases to 0.26€/minute (-19%) and the gain in welfare to 6.15€ (-10%). If we keep increasing the number of connecting passengers the cost of delay keeps decreasing. Still, almost no effect is observed over optimal buffer times and gains in welfare. Also, a reduction or an increase in the number of connecting passengers will be clearly accompanied by a reduction or increase in the minutes of extra delays introduced to wait for connecting passengers which implies an opposite effect over the calibration of buffer time.

## VIII. CONCLUSIONS

Delays constitute a widespread relevant phenomenon in air-transportation. This paper is a first-attempt to make precise the issues at stake, in order to draw a consistent policy. It also provides a methodology to estimate social costs of delays. The later is illustrated by the means of a simple calibration.

We consider a situation where there is a single, profit-maximizing operator. Complex pricing schemes do not come as an issue since we adopt a representative agent approach. All passengers have the same value of time and, for each city-pair, demand is actually derived from quasi-linear preferences as represented by quadratic utilities. With this simple yet (in our view) realistic model, we obtain very clear-cut results from a calibration exercise performed with exhaustive data over a two-month period. Airlines should decrease their buffer delays. That is to say socially optimal schedule would result in shorter journeys but more apparent delays.

The effects over welfare of these changes appear however to be quite small. There are several reasons to this. First, there is a low number of connecting passengers over the sample and all the cities of the network enjoy a relatively frequency of services. Second, the (endogenously determined) passengers' value of time appears to be low. Third, and more importantly, scheduling is only one dimension of the analysis. As long as pricing is not subject to any constraint, firms appear to be able to extract a fair amount of consumer (gross) surplus. Thus, because an increase in consumer surplus ultimately leads to an increase in their profits, airline account for travelers benefits while taking their scheduling decisions. This is to say: the only difference between profit-maximizing and socially optimal scheduling stream from pricing imperfections.

Overall and in any case, the new EU policy on compensation for long delays appears to be quite inadequate. More precisely, it should either be ineffective or result in reduced social welfare.

This paper presents several limits. First, as a consequence of the representative agent approach, travelers have an identical value of time. It follows that market segmentation is

exogenous. Would consumers have had heterogeneous characteristics, optimal choice theory would have indeed provided a natural endogenous split of travelers across available services. Second, passengers are risk neutral. This is obviously a point to take into account and we plan to look at the consequences of risk aversion in the near future. Observe however that the latter can only change numerical estimates. All conclusions drawn here are robust to the introduction of risk aversion as they do not hinge upon the particular values attached to time losses. They directly follow from the economic mechanisms at hand.

Finally, some may point to the monopoly assumption as being quite restrictive. Yet, according to Tournut (2004), 60% of the routes in the world are operated through a monopolistic position. And, according to Billette de Villemeur (2004), the figure raises to 85% for the routes over the French territory. Obviously, optimal delays (hence costs) depend upon market situation. Thus, whenever competition occur (within the air-transportation mode or across transportation modes), it has to be taken into account in order to derive consistent empirical estimates. That said, we are pretty sure that our main conclusions would convey with such enrichment of our model.

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#### REFERENCES

- [1] Bates, J., Polack, J., Jones, P., and A. Cook, (2001): "The Valuation of Reliability for Personal Travel", *Transportation Research Part E*, 37, 191-229.
- [2] Betancor, O., and G. Nombela (2002): "Mohring Effects for Air Transport", *Annex to Deliverable 7 Transport User Costs and Benefits. UNITE project*, European Commission, DG TREN.
- [3] Billette de Villemeur, E. (2004): "Regulation in the Air: Price-and-Frequency Caps", *Transportation Research Part E*, 40, 465-476.
- [4] Brueckner, J. K. (2002): "Airport Congestion When Carriers Have Market Power", *The American Economic Review*, 92, 1357-1375.
- [5] Brueckner, J. K. (2003): "Internalization of Airport Congestion: A Network Analysis", *International Journal of Industrial Organization*, 23, 599-614.
- [6] Brueckner, J. K., and Zhang, Y. (2001): "A Model of Scheduling in Airline Networks: How Hub-and-Spoke System affects Flight Frequency, Fares and Welfare", *Journal of Transportation Economics and Policy*, 35, 195-222.
- [7] Carlin, A., and Park, R. (1970): "Marginal Cost Pricing of Airport Runway Capacity", *The American Economic Review*, 60, 310-319.
- [8] Daniel, J. I. (1995): "Congestion Pricing and Capacity of Large Hub Airports: A Bottleneck Model with Stochastic Queues", *Econometrica*, 63, 327-370.
- [9] De Palma A., and D. Rochat (1996): "Urban Congestion and Commuters Behaviour: The Departure Time Context", *Revue d'Economie Régionale et Urbaine*, 3, 467-488.
- [10] Eurocontrol, Ecoda (2005): "Delays to Air Transport in Europe Annual Report 2004" Brussels.
- [11] European Commission (2001): "White Paper: European Transport Policy for 2010: Time to Decide", COM 370, Brussels.
- [12] European Commission (2005): "Strengthening Passenger Rights within the European Union", COM46, Brussels.
- [13] Institut du Transport Aérien (2000): "Costs of Air Transport Delay in Europe", Paris.
- [14] Mayer, C. and T. Sinai (2003): "Network Effects, Congestion Externalities, and Air Traffic Delays: Or Why Not All Delays Are Evil" *The American Economic Review*, 93, 1194-1215.
- [15] Morrison, S. A., Winston, C., Bailey, E., and A. Khan (1989): "Enhancing the Performance of the Deregulated Air Transportation System", *Brooking Papers on Economic Activity*. Microeconomics, 1989, 61-123.
- [16] Morrison, S. A. and C. Winston, (2007): "Another Look at Airport Congestion Pricing", *The American Economic Review*, 97, 1970-1977.
- [17] Noland, R., and J. Polack (2002): "Travel Time Variability: A Review of Theoretical and Empirical Studies", *Transport Reviews*, 22, 39-54.
- [18] Nombela, G., de Rus, G. and O. Betancor (2002): "Evaluation of Congestion Costs for Madrid Airport", *Annex 7i UNITE*.
- [19] Nombela, G., de Rus, G., and O. Betancor (2004): "Internalizing Airport Congestion", *Utilities Policy*, 12, 323-331.
- [20] Neven, D. J., Röller, L., and Z. Zhang (2006): "Endogenous Costs and Price-Cost Margins: An Application to the European Airline Industry", *Journal of Industrial Economics*, 54, 351-368.
- [21] Park, E. (1971): "Congestion Tolls for Commercial Airports", *Econometrica*, 39, 683-694.
- [22] Schank, J. L. (2005): "Solving Airside Airport Congestion: Why Peak Runway Pricing is Not Working", *Journal of Air Transport Management*, 11, 417-425.
- [23] Tournut, J. (2004): "Monopoly and optimal nonlinear pricing: the case of route monopolies and heterogeneous demand in the air transport market", *Transportation Research Part E*, 40, 477-513.
- [24] University of Westminster (2004): "Evaluating the True Cost to Airlines of One Minute of Airborne or Ground Delay", Performance Review Commission, Eurocontrol.