# THE PROBLEM OF CHARGING CONGESTION AT AN AIRPORT: WHAT IS THE POTENTIAL OF MODELLING?

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## ABSTRACT

The charging congestion at an airport represents internalising of the costs of the system marginal delays imposed by an additional aircraft on the succeeding aircraft during the congestion period.
This paper investigates the potential of modelling charging of congestion at an airport. For such purpose a convenient model consisting of two sub-models is developed. The first sub-model based on the diffusion approximation of queues is used to estimate congestion and aircraft/flight delays, which might be the matter for charging at a given airport. Another sub-model is intended to estimate feasibility of operating the aircraft/flight at an airport with the internalised congestion.

The model inputs are the characteristics of the aircraft/flights in terms of the scheduled arrival time, duration (short, medium, long-haul), seat capacity, the number of passengers on board, operational cost and revenues. The model outputs are the total and marginal queues, delays and corresponding costs.

*KEY WORDS: airport, charging congestion, modelling, diffusion approximation of queues*

## 1 INTRODUCTION

Congestion and aircraft/flight delays in the air transport systems of both Europe and U.S. have generally increased over the past decade. The most obvious have been growing demand, constrained infrastructure capacity, and unplanned disruptions of airline schedules (Janic, 2003). The congestion and delays due to an imbalance between air transport demand and infrastructure capacity has generally been alleviated by improvements of utilisation of existing capacity, physical expansion of infrastructure, and demand management. The first option has shown to have the limited effect. In many cases, implementation of the second option has been difficult or even impossible at least in the in the short-term due to the various political and environmental constraints in terms of noise, air pollution and land use. The last option, demand management has recently been considered as potentially viable option to relieve the congestion problem (Adler, 2001; DeCota, 2001; FAA, 2001).

In addition to the institutional instruments, demand management at airports embraces the economic instruments such as charging of congestion and auctions of slots. In general, a central problem of dealing with charging of congestion consists of recognising the right case (i.e., the type and nature of congestion) and an estimation of the marginal delay costs imposed by an additional flight to all subsequent flights during the given congested period. In such a context, this additional flight has to pay (theoretically) its private delay costs and a charge equivalent to the marginal costs of delays imposed on the all-subsequent flights. This charge may raise the total flight operating costs and consequently compromise its profitability. Currently, the charging system at European and U.S. airports is mainly based on the aircraft weights and has a little in common with the above-mentioned concept of charging congestion (ACI, 2001; Adler, 2002; Doganis, 1992).

This paper develops a model for charging congestion at an airport. In addition to this introduction, the paper consists of four sections. Section 2 provides an insight into the problem of congestion at particular European and U.S airports. Section 3 elaborates the conditions under which charging of congestion could be implemented. Section 4 deals with modelling procedure. Section 5 provides an application of the proposed model. Section 5 contains some conclusions.

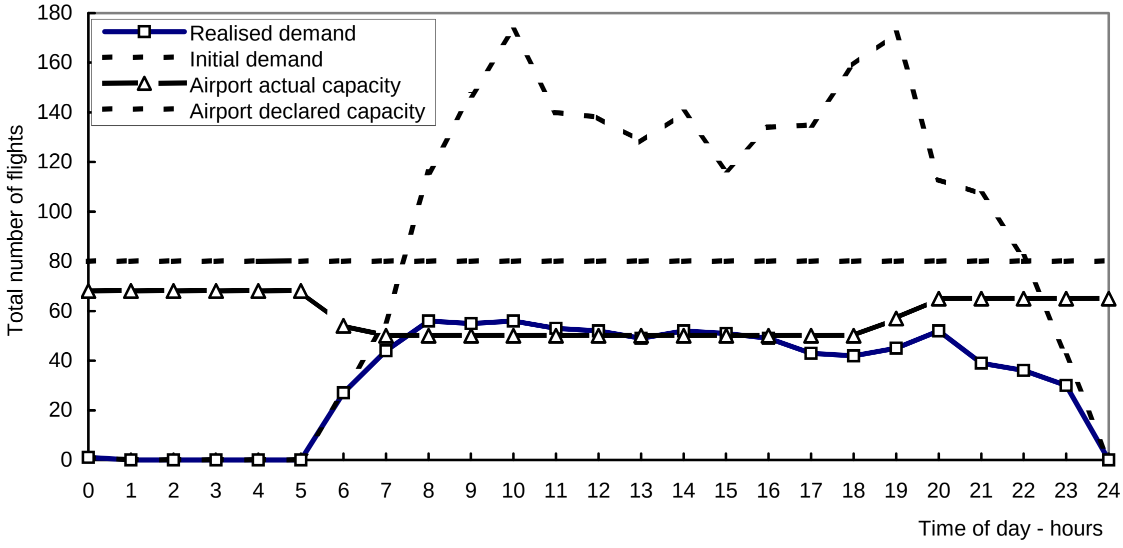
## 2 DEMAND, CAPACITY AND CONGESTION AT AIRPORTS IN EUROPE AND UNITED STATES

Dealing with charging of congestion at airports should include an analysis of the relevant parameters such as demand, capacity and congestion. Demand is represented by the flights schedule at an airport carried out by one or more airlines. At many large European and U.S. hub and non-hub airports, one (incumbent) or few (competing) airlines, their subsidiaries and alliance partners carry the flights out. These flights use the available arrival and departure slots, i.e., the airport declared (practical) capacity to get service at the airport. In Europe, the maximum number of arrival and departure flights accommodated at an airport during given period of time (usually one hour) under given conditions determines the airport declared (practical) capacity. This capacity is based on IMC (Instrumental Meteorological Conditions) and IFR (Instrumental Flight Rules). Usually, this capacity is an agreed value between airlines, airports and air traffic control (EUROCONTROL, 2002). In the U.S., the airport capacity has usually two values: the higher under VMC (Visual Meteorological Conditions) and VFR (Visual Flight Rules), and the lower under IMC and IFR (FAA, 2001).

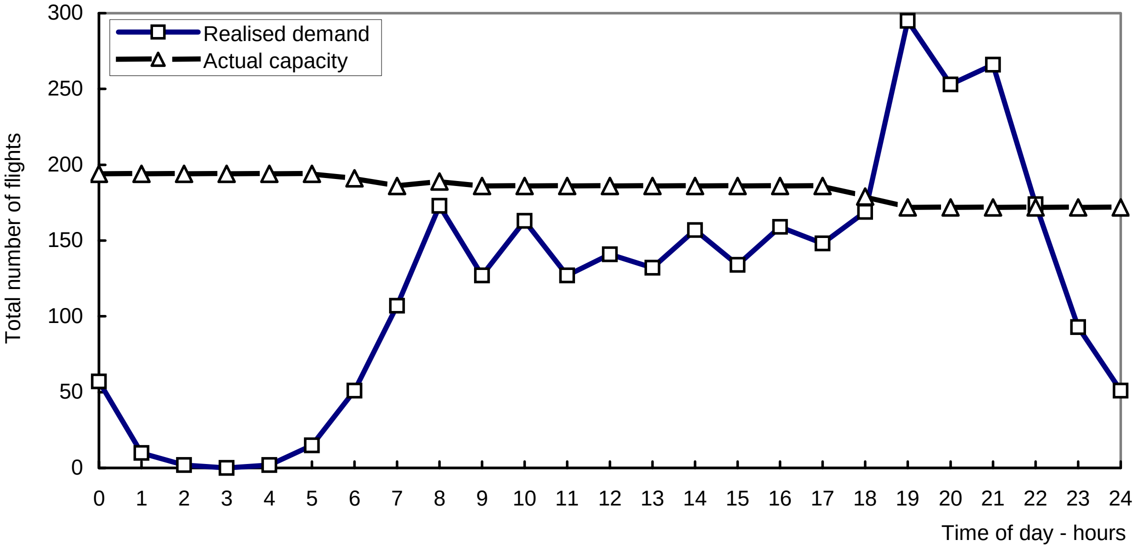
### 2.1 Demand and capacity

Many large and congested European and U.S. airports are “slot-controlled”. This implies that the number of flights/aircraft is balanced with the airport declared capacity in order to maintain congestion and flight/aircraft delays under prescribed boundaries. At these airports, the initial demand and the available airport capacity are balanced through the multi-stage process of negotiations between airlines, airports and air traffic control. In such context, the demand is generally allowed to raise at most to the level of airport capacity over the longer period of time (day), which, under regular operating conditions enables planned congestion and delays. However, due to the system imperfectness and other disrupting factors, the actual demand frequently exceeds the airport declared capacity and consequently causes unexpectedly longer congestion and delays (ATA, 2002, EUROCONTROL, 2002, FAA, 2001, 2002a; Liang et al., 2000; Janic, 2003).

Figure 1a illustrates an example of two-stage balancing of demand and capacity at New York LaGuardia airport (U.S) during a peak day, 30 June 2001 (beginning of the Independence Day holiday) (FAA, 2002a).



**a)** New York LaGuardia airport



**b)** Atlanta Hartsfield airport

**Figure 1** Relationship between demand and capacity at two U.S. airports (Compiled from FAA, 2002a)

As can be seen, at the first stage the initial demand consisting of flights of about twenty competing airlines was much higher than the airport actual capacity (which was lower than the declared capacity). At the second stage, the demand was suppressed below the declared capacity but remained slightly above the actual capacity during the morning and early afternoon hours.
Figure 1b illustrates the relationship between the airport demand and capacity at the U.S. Atlanta Hartsfield airport during the same day, 30 June 2001. As can be seen, the pattern of demand was quite different than at LaGuardia airport due to different – hub-and-spoke – operations of the

main incumbent Delta Airlines. In the morning and afternoon hours the realised demand has been lower than the actual capacity. However, it exceeded this capacity (which also changed during the day) considerably during the late afternoon and evening hours.

In both above-mentioned examples, the relationships between demand and capacity imply congestion. However, this congestion is of the distinctive nature. In the former case, many competing airlines use the airport as origin and destination of their flights. In such case, congestion occurs mainly due to the competition. In the later case, an incumbent uses the airport as its hub and intentionally creates congestions by the hub-and-spoke operational pattern. However, in both examples, the level of congestion is negotiated and consequently the access to the airports controlled.

## 2.2 Congestion and delays

The congestion causes flight delays. In general, delay is defined as the difference between the actual and scheduled time at the 'referent location'. The threshold for either arrival or departure flight delay is the period longer than 15 minutes behind the schedule (AEA, 2001; BTS, 2001; EUROCONTROL, 2001; FAA, 2002a,).

Congestion and delays have become common (and inherent) operational characteristic at many European and U.S. airports,. Table 1 shows some relevant statistics. As can be seen, the proportion of delayed flights has been different in both regions. In Europe, it has varied between 17% and 30% for arrivals, and from 8% to 24% for departures. In the U.S., this proportion has varied between 22% and 40% for arrivals, and from 19% to 38% for departures. In general, more frequent delays have taken place at the U.S. than European airports.

**Table 1** Delays at some congested European and U.S. airports

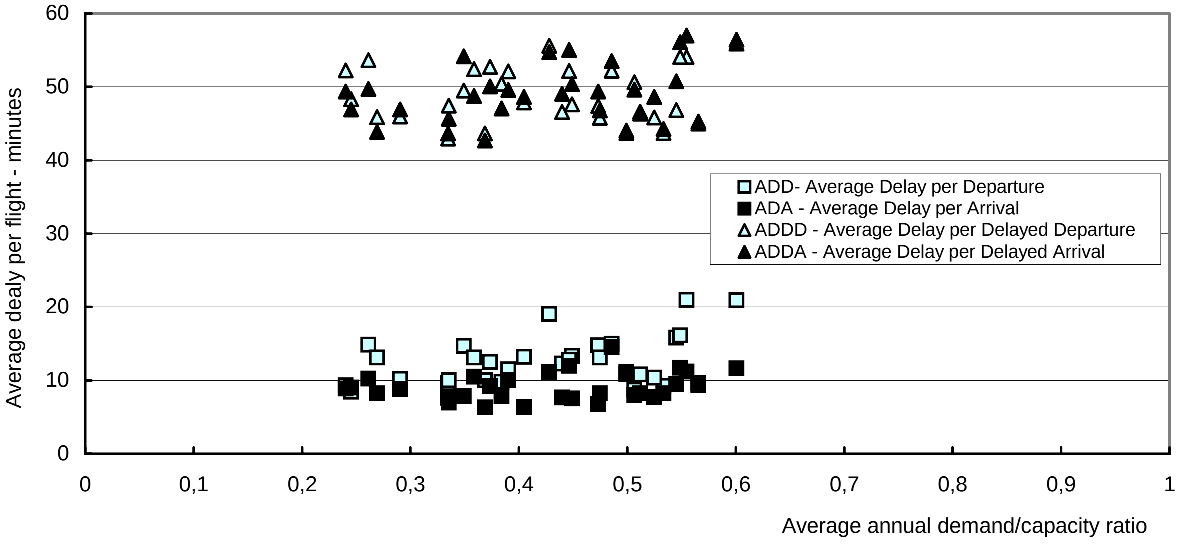
| ***European airports (2001)*** | ***(%) of delayed flights*** | | | ***U.S. airports (1999)*** | ***(%) of delayed flights*** | |
|---|---|---|---|---|---|---|
| | ***Arrivals*** | ***Departures*** | | | ***Arrivals*** | ***Departures*** |
| Paris CDG | 24.6 | 21.8 | | Chicago-O'Hare | 33.6 | 29.9 |
| London Heathrow | 17.4 | 21.0 | | Newark | 38.4 | 31.0 |
| Frankfurt | 30.8 | 18.9 | | Atlanta | 30.9 | 26.8 |
| Amsterdam | 25.7 | 23.2 | | NY-La Guardia | 40.1 | 28.9 |
| Madrid/Barajas | 19.6 | 20.0 | | San Francisco | 32.1 | 21.5 |
| Munich | 19.0 | 19.0 | | Dallas-Ft. Worth | 21.7 | 23.7 |
| Brussels | 29.8 | 27.7 | | Boston Logan | 37.7 | 29.3 |
| Zurich | 23.2 | 23.8 | | Philadelphia | 40.4 | 37.9 |
| Rome/Fiumicino | - | 12.5 | | NY-Kennedy | 28.0 | 19.0 |
| Copenhagen/K | 17.8 | 10.3 | | Phoenix | 29.6 | 30.8 |
| Stockholm/Arlanda | - | 8.0 | | Detroit | 24.6 | 26.3 |
| London/Gatwick | 19.6 | 24.3 | | Los Angeles | 26.1 | 20.8 |

*Sources: EUROCONTOL/ECAC, 2002; FAA, 2002a*

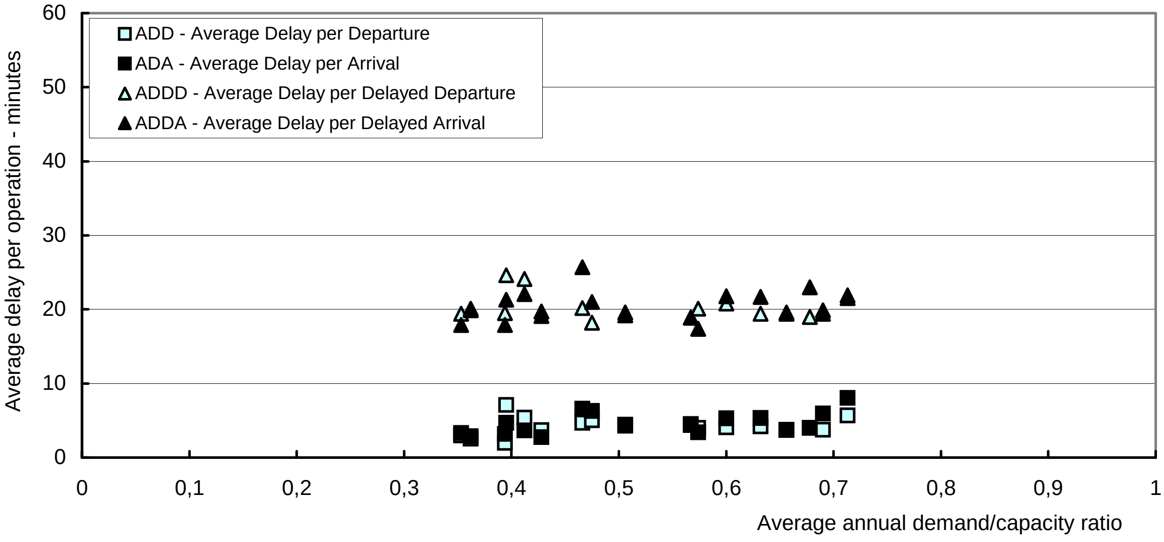
Delays at airports are generally expressed as the average time per flight or the average time per delayed flight (the total delay divided by the number of all or by the number of only delayed flights per period, respectively) (EUROCONTROL/ECAC, 2002; FAA, 2002a).

In addition, total delays are always segregated into the arrival and departure delays. Figure 2 (a and b) shows both types of delays in dependence on the average annual demand/capacity ratio (i.e., utilisation of airport capacity) for 32 U.S. and 17 European the most congested airports.

As can be seen, the average delay per flight – either departure or arrival - has been generally longer at the U.S than European airports. At the U.S. airports, the departure delays have generally been longer than the arrival delays. The former has varied between 10 and 20, and the later between 5 and 15 minutes. At European airports, there has not been obvious distinction between the average delay per an arrival and a departure flight. Almost all delays have been shorter than 10 minutes.



**a)** U.S. Airports (Source: FAA, 2002a)



**b)** European airports (Source: EUROCONTROL/ECAC, 2002)

**Figure 2** Dependability between the average flight delay and the average utilisation of the airport capacity

According to the threshold of 15 minutes, flights in both samples should not be considered delayed at all. In both regions, the very slight increasing of delays for both types of operations with increasing of the demand/capacity ratio has been noticeable.

The picture changes when the average delay per delayed flights is considered. In given sample, this delay has again appeared longer at the U.S. than European airports, 40-60 minutes compared to 15–25 minutes, respectively. In both regions, this delay has been similar for both types of operations and seemingly non-influenced by the airport utilisation (i.e., the demand/capacity ratio). According to threshold of 15 minutes, these have been counted as delayed flights. In the U.S., on average, bad weather has caused about 70-75% and congestion about 20-30% of these delays (BTS, 2001; FAA, 2001; 2002a). In Europe, on average, severe weather has caused only 1-4% and congestion about 30-40% of these delays (AEA, 2001; EUROCONTROL, 2001).

Figure 2 (a and b) also shows that the average utilisation of the airport capacity has varied between 25% and 65% at the U.S. and between 35% and 75 % at European airports. This indicates that at almost all airports the demand has always been kept below the capacity at an annual scale, as a rule for preventing extreme congestion and delays (Welch and Lloyd, 2001; Odoni and Fan, 2001).

## 3 CHARGING CONGESTION AT AIRPORTS

### 3.1 Background

Interaction between demand and capacity, which causes congestion at airports is commonly measured by the ratio between the intensity of demand and capacity (or the capacity utilisation ratio). This ratio can generally take the values lower, equal or greater than one. Specifically, if the intensity of demand equalises with the capacity, this ratio takes the value 1.0 (or 100%)(Newell, 1982). At most European and U.S congested airports, contrary to the above-mentioned annual averages, the utilisation ratio during the short peak periods of a quarter or an hour often reaches or even exceeds the value 1.0 (100%), particularly. This implies significant congestion and delay[1] (FAA, 2001; 2002a). When this ratio cannot be institutionally regulated (i.e., negotiated) the economic instruments of demand management, one of which is the charging congestion could be considered (Vickery, 1969).

### 3.2 Inherent complexity of implementation

Up to date, despite being theoretically matured clear and warmly recommended by the academic economics and policy-making literature, charging of congestion at airports has still not found practical application. The main causes could be summarised as 'collision with the overall airport objectives including the lack of real cases', 'complexity of measurement', 'ambiguity of the concept' and 'barriers within the industry'.

#### *3.2.1 Collision with the airport objectives and the lack of real cases*

Most airports worldwide have always tended to grow under given circumstances due to their internal (economic) as well as wider external (economic and political) regional and national interests. The growth has assumed attraction of as great as possible traffic. Under such circumstances, physical expansion of infrastructure capacity has always been used as the most

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[1] It is well known that if demand/capacity ratio is lower or close to 1.0 (100%), congestion occurs mainly due to the random variability of the flight inter-arrival and service time. If this ratio is greater than 1.0 (100%), the excessive demand dominates as the cause of congestion (Newell, 1982).

feasible long-term solution for relieving congestion despite the various short-term social, political and environmental barriers. Consequently, airports have very rarely considered charging of congestion as a viable short-term remedy. The revenues from combined aeronautical[2] and non-aeronautical charges have provided coverage of the airport operational costs and partly for funding the investments.

### *3.2.2 Complexity of measurement of conditions*

Many simultaneous causes have usually caused congestion materialised as peaks, which have differ at particular airports in terms of 'frequency and duration' and 'type of operations and aircraft involved'.

In terms of the *frequency and duration*, the short and frequent peaks have been created by the airline hub-and-spoke operations. The long and infrequent peaks have been created by the large demand exceeding the capacity during several hours of the day.

In terms of *type of operation and aircraft*, congestion during the peaks have affected both arrival and departure flights and sometimes transferred delays between them. The same or different aircraft types of either co-operating or competing airlines have carried out these flights.

Extraction of real causes for charging congestion has shown to be complex or even impossible task. There has been the lack of criteria for setting up the relevant level of congestion and delays to be charged (internalised). Since delays up to the threshold of 15 minutes have not been counted, only the longer ones (but which?) have deserved to be internalised (Airport Council International, 2001, Odoni and Fan, 2001; Janic, 2003). Internalising of congestion within the airline hub-and-spoke operations or due to disruptions of the airport capacity, which might cause delays longer than 15 minutes has been questionable. In the former case, the internalisation could compromise integrity of the airline schedule. In the later case, internalising of congestion caused by the factors out of control of airlines airports and air traffic control could be difficult to justify.

### *3.2.3 Ambiguity of the concept and barriers within the industry*

Charging congestion at airports seems to be ambiguous. Actually, it is supposed to impose a charge equivalent to the cost of marginal delay cost, which an additional flight imposes on the succeeding flights during the congestion period. The objective is to deter (i.e., prevent) access of such flight and all other similar flights. This seems to be in collision with the guaranteed freedoms of the unlimited access to the "slot uncontrolled" airports (Corbett, 2002). In addition, this charge is supposed be effective, which in the case of imperfection of the real market might not be true. The charge simply may either be too low to be effective, or too high to unwillingly suppress the elastic demand. As well, the relation between this and other airport externalities such as noise and air pollution, as well as the relation of this with existing charging schemes based on the aircraft take-off weight are not clear and transparent. Furthermore, there may be a problem of spending the collected charges. First, the affected airlines suffering additional costs can use them. Second, if they would be used for increasing of the airport capacity, the source of the revenues – congestion – could vanish. Third, it seems difficult and sensitive to impose the additional charges to the economically and financially vulnerable airline industry. Last but not least, if the charge works asa deterring tool the additional money will not be collected and the only benefit will be less delays and associated costs of the accommodated flights. It is less likely to consider allocation of this money outside the industry.

All above reasons have contributed to building up the opposition against congestion charging. Adler (2002) has identified three groups of barriers as follows:

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[2] A part of the aeronautical charges has consisted of landing fees based on the aircraft weight (ACI, 2001).

- Institutional, organisational, political and legal barriers maintained by the monopolistic powerful hub airports (Europe) and powerful airlines (both in Europe and U.S.). This also includes the lack of harmonisation of charging conditions across the countries (Europe) and across the airports of different size (both in Europe and U.S.);
- Unacceptability of the concept for large airlines and their alliances (lobby groups) due to the lack of similar concepts at most other transport modes (both in Europe and the U.S.); and
- Unavailability of the relevant data on the actual causes of congestion at airports including the precise data on the changes of airport capacity (Europe). Relatively useful databases already exist in the U.S. (FAA, 2002a).

## 4 A MODEL OF CHARGING CONGESTION AT AN AIRPORT

### 4.1 State of the art

A long time ago, the economic theory noted that optimal use of a congested transport facility – in this case an airport – could not be achieved unless each user (flight) was forced to pay the marginal delay cost it imposed on all other subsequent users (flights) during the congestion period. In the nineties, the cost of marginal delay has been considered as an externality to be internalised together with others such as air pollution, noise and air traffic accidents (Adler, 2002; Brueckner, 2002; Daniel, 1995; Daniel and Pahwa, 2000; Daniel, 2001; EC, 1997; ECMT, 1998; Odoni and Fan, 2001; Vickery, 1969). In such context, some researchers proposed charging of the marginal delays caused by the hub-and-spoke operations. They used the steady-state and time-dependent, analytically efficient and attractive, queuing models to estimate the cost of congestion and delay to be internalised. Nevertheless, it was not quite clear why alleviation of peaks by charging congestion was suggested since the airport airlines and passenger already balanced their interests within the given circumstances (Daniel, 1995; Daniel, 2001). Nevertheless, comparison of different models of charging the airport congestion produced some interesting results on their performances (Daniel and Pahwa, 2000). In addition, some research also tackled the problem of charging the airport congestion when the airlines with different market shares already internalised their congestion costs (Bruckener, 2002).

Despite being theoretically sophisticated, almost all above (economic) models remained within the academic domain. With partial exception of the work of Daniel (1995; 2001) and Brueckner (2001), one of the factors was related to making an analogy between the congested roads and airports, where the only similarity shown to be type of the 'predictable' queues (Hall, 1991). In addition, the models assumed that a charge based on the marginal delay cost would be effective. As well, some recent research suggested implementation of the congestion charge (in addition to other externalities) non-selectively - at all or almost all European airports, which could face the strong opposition of both airports and airlines (Adler, 2002).

### 4.2 Assumptions

In this paper, modelling of the congestion charges at an airport as a continuation of the previous research is based on following assumptions:

- The time–varying demand and capacity profile at the candidate airport are known during typical (representative) day. The demand profile can be obtained from the published airport (and airline) schedule(s). In such context, each flight is considered with respect to the average operational costs and revenues. The capacity profile(s) can be obtained from the airport or air traffic control operator for given conditions (IMC or VMC). This capacity reflects the average service time of particular arriving and departing flights. The runway system is assumed as critical element of congestion.

- Only the congestions during the long peaks in which the demand/capacity ratio is close to or exceeding 1.0 (100%) is considered for internalising. This assumption can be used for selection of the candidate airports (Adler, 2002).

The number of flights constitutin congestion during such long peaks is assumed to be large (at least several dozens), which makes congestion mainly dependent on the predictable variations (and positive differences) between the demand and capacity[3]. This makes application of the diffusion approximation of queues for estimation of congestion and delays convenient (Hall, 1991; Newell, 1982).

## 4.4 The model structure

### *4.4.1 Estimating the queues at a congested airport*

Charging congestion at an airport requires estimation of the system marginal delay, which consists of the sum of i) the private cost of delay of an additional flight, and ii) the cost of marginal (additional) delays, which this flight imposes on the succeeding flights during the congested period (Ghali and Smith, 1995; Hall, 1991). Both delays can be estimated by using the various queuing and simulation models (Hall, 1998; Newell, 1982; Odoni et al., 1997). In these models, congestion is usually related to the time-dependent demand/capacity ratio $\rho(t)$. At time $(t)$, $\rho(t) = \lambda(t)/\mu(t)$ where $\lambda(t)$ is the flight arrival rate (i.e., demand for service) and $\mu(t)$ is the flight service rate (i.e., capacity). Different techniques are developed to estimate congestion and related delays in dependence on $\rho(t)$. One of them, a graphical representation of the typical queuing process at the congested facility (an airport) during period *T* (one day) is shown in Figure 3.

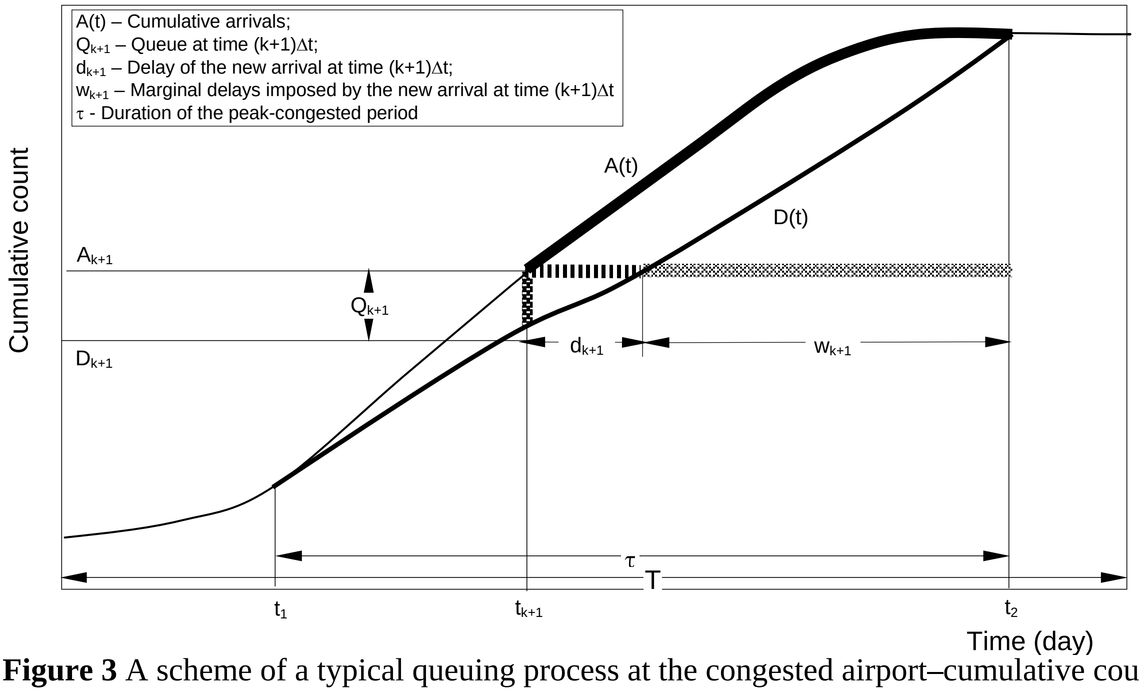

**Figure 3** A scheme of a typical queuing process at the congested airport–cumulative count of flights

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[3] For example, for the non-stationary Poisson arrival/departure processes, if the number of users-customers during given period is greater, the smaller will be the random variations of this number (Hall, 1991).

The curves $A(t)$ and $D(t)$ represent the cumulative counts of flights requesting service and being served, respectively, by time $(t)$. Since the number of flights in the system is assumed to be large (>> 1.0) both types of counts, actually the step functions of time, can be considered as their continuous (smooth) counterparts. Consequently, $\lambda(t) = dA(t)/dt$ and $\mu(t) = dD(t)/dt$. The functions $A(t)$ and $D(t)$ may relate only to one realisation or be the averages of many daily realisations of serving the flights at the congested airport(s). Dependent on the relationships between two curves, three sub-periods can be identified. In the first one $(0, t_1)$, $A(t)$ lies below $D(t)$ and $\rho(t)$ is less than $1.0$. In this case only the "random effects" cause congestion. During the second sub-period $(t_1, t_2) \equiv \tau$, $A(t)$ exceeds the curve $D(t)$. The values of $\rho(t)$ fluctuate from being equal, greater, again equal, and finally less than one. In this case, 'deterministic effects' are the main causes of congestion while the previously important 'random effects' are negligible. Finally, during the sub-period $(t_2,T)$, $A(t)$ again drops bellow $D(t)$ and the similar developments as in the first sub-period take place.

Obviously, only congestion during the period $(\tau)$ should be under internalising since it certainly may produce delays longer than the threshold of 15 minutes (Hall, 1991; Newell, 1982). To estimate these congestion and delays, the period $(\tau)$ is divided into $K$ equal increments $\Delta t$ (i.e., $K*\Delta t \approx \tau$). As compared to $(\tau)$, each increment $\Delta t$ should be sufficiently short[4] in order to register changes of the congestion and delays on the one hand, and sufficiently long to guarantee the independence between the cumulative flight arrival and departure processes and their independence during the successive increments on the other. Thus, two processes $A(t)$ and $D(t)$ can be treated as the processes of independent increments or the diffusion processes (Newell, 1982). Under an assumption that the differences between the cumulative flight demand and corresponding airport capacity in $(k)$th and $(k+1)$st time increment $\Delta t$, $A(k+1) - A(k) \equiv A_{k+1} - A_k$ and $D(k+1) - D(k) \equiv D_{k+1} - D_k$, respectively, are considered as the stochastic variables with the normal probability distribution, the difference $Q_{k+1} = A_{k+1} - D_{k+1}$, which represents the queue in $(k+1)$st increment $\Delta t$, will also be the stochastic variable with normal probability distribution $(k \in K)$ (Newell, 1982). Consequently, the flight queue in $(k+1)$st interval $\Delta t$, can be approximated as follows:

$$Q_{k+1} = Q_k + \overline{Q}_{k+1} + B_{k+1} = Q_k + (\lambda_{k+1} + \mu_{k+1})\Delta t + B_{k+1} \text{ for } k = 0, 1, 2, , , , K\text{-}1 \qquad (1)$$

where

| | |
|---|---|
| $Q_k$ | is the queue in $(k)$th increment $\Delta t$; |
| $\overline{Q}_{k+1}$ | is the average queue in the $(k+1)$st increment $\Delta t$; |
| $\lambda_{k+1}$ | is the intensity of flight demand in $(k+1)$st increment $\Delta t$; |
| $\mu_{k+1}$ | is the airport capacity (i.e., the flight service rate) in $(k+1)$st increment $\Delta t$; |
| $B_{k+1}$ | is the anticipated deviation of the actual flight queue (i.e., a "buffer") from its average in $(k+1)$st increment $\Delta t$. |

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[4] For example, if $(\tau)$ is the period of several hours during the day, $\Delta t$ will certainly be quarter, half or an hour.

As can be seen, the average flight queue either increases or decreases accordingly as $\lambda_{k+1} > \mu_{k+1}$ or $\lambda_{k+1} < \mu_{k+1}$.

The anticipated deviation $B_{k+1}$ in the expression (1) can be estimated as follows (Newell, 1982):

$$B_{k+1} \cong \sqrt{\Delta t(\sigma^2_{a,k+1}/\bar{t}^3_{a,k+1} + \sigma^2_{d,k+1}/\bar{t}^3_{d,k+1})} * C \quad \text{for } k = 0, 1, 2, \ldots, K\text{-}1 \qquad (2)$$

where

| | |
|---|---|
| $\bar{t}_{a,k+1}; \bar{t}_{d,k+1}$ | is the average flight inter-arrival and service time, respectively, in $(k+1)$st increment $\Delta t$; |
| $\sigma_{a,k+1}; \sigma_{d,k+1}$ | is the standard deviation of the flight inter-arrival and service time, respectively, in $(k+1)$st increment $\Delta t$; |
| $C$ | is constant ($C = \Phi^1(1\text{-}p)$, where $\Phi^1$ is the inverse Laplace's function and $p$ is the probability that the flight queue in $(k+1)$st increment $\Delta t$ will spill out of the confidence interval $(\overline{Q}_{k+1} \pm B_{k+1})$. |

In the expression (2), the variance of distributions of the flight inter-arrival and service time are assumed to be independent in the successive $(k)$th and $(k+1)$st increment $\Delta t$ (Newell, 1982):

In expression (1) and Figure 3, at the beginning of period $(\tau)$, the intensity of flight demand becomes equal to the capacity for the first time, and the deterministic queue starts to build up. However, this queue continues to the queue already built up due to the previously dominating 'random effects'. The later queue $\overline{Q}_0$ can be approximated as follows (Newell, 1982):

$$\overline{Q}_0 \equiv Q_{m/(\lambda_m=\mu_m)} = \left\{\left(\frac{1}{\left[(\sigma_{a.m}/\bar{t}_{a,m})^2 + (\sigma_{d,m}/\bar{t}_{d,m})^2\right]^2}\right) * (1/\mu_m) * (d\rho_m/dt)\right\}^{-1/3} \qquad (3)$$

where

| | |
|---|---|
| $m$ | is the index of time increment $\Delta t$ in which the intensity of flight demand becomes equal to the flight service rate (i.e., capacity) ($m \in K$). |

Other symbols are analogous to those in the previous expressions.

### *4.4.2 Determining the system delays and costs*

From expressions (1)–(3), delay of a flight joining the queue in $(k+1)$st increment $\Delta t$ can be approximated as follows:

$$d_{k+1} = Q_{k+1} * (\bar{t}_{d,k+1} + B_{d,k+1}) = Q_{k+1} * \left[\bar{t}_{d,k+1} + \sigma_{d,k+1} * \Phi^{-1}(1-p)\right] \qquad (4)$$

where the symbols are analogous to those in the previous expressions.

Expression (4) assumes that the flight service rate (i.e., the airport capacity) does not change during serving the queue $Q_{k+1}$.

In Figure 3, the marginal delay, which an additional flight arrived during *(k+1)*st increment *Δt* imposes on all subsequent flights until the end of the period *(τ)* can be determined as:

$$
\begin{aligned}
w_{k+1} &\cong \tau - [(k+1)\Delta t + d_{k+1}] \equiv (\bar{t}_{d,k+1} + B_{d,k+1}) * \sum_{l=k+1}^{K} [1/(\bar{t}_{a,l} + B_{a,l}] * \Delta t = \\
&= [\bar{t}_{d,k+1} + \sigma_{d,k+1} * \Phi^{-1}(1-p)] * \sum_{l=k+1}^{K} \{1/[\bar{t}_{a,l} + \sigma_{a,k} * \Phi^{-1}(1-p)]\} * \Delta t
\end{aligned}
\tag{5}
$$

where all symbols are analogous to those in the previous expressions.

From the expression (5), the marginal delay, which the additional flight imposes on the succeeding flights, is proportional to the product of its service time (i.e., the airport flight service rate - capacity - at the time it takes place) and the number of the succeeding - affected - flights. Diminishing of the airport capacity combined with its increased volatility will certainly increase the marginal delays. As well, if the additional flight is scheduled closer to the beginning of the peak, more succeeding flights will be affected and marginal delays longer, and vice versa.

If the additional flight belongs to the group of $N_i(\tau)$ uniformly distributed flights scheduled by airline *(i)* during the peak *(τ)* in addition to the flights of other *M-1* airlines, i.e., $N(\tau) = \sum_{i=1}^{M} N_i(\tau) \equiv A(\tau)$, the total cost it imposes to all succeeding flights can be determined as follows:

$$
C^{i}_{m,k+1} = [1 - N_i(\tau)/N(\tau)] * [\bar{t}_{d,k+1} + \sigma_{d,k+1}\Phi^{-1}(1-p)] * \sum_{l=k+1}^{K} c_l * \{1/[\bar{t}_{a,l} + \sigma_{a,l}\Phi^{-1}(1-p)]\} * \Delta t \tag{6}
$$

where

$c_l$ is the average cost per unit of delay of a flight scheduled in *(l)*th increment *Δt* (in the monetary units per unit of time).

Other symbols are analogous to those in the previous expressions.

The cost per flight $c_l$ may include the aircraft operational and passenger time costs. Expression (6) shows that the total marginal cost imposed by the additional flight of airline *(i)* on the succeeding flights will increase with decreasing of the airport service rate (capacity) and increasing of its volatility. In addition, this cost will rise with increasing of the number and size (expenses) of flights involved in the peak. As well, under the other fixed conditions, this marginal cost will decrease with increasing of the number of flights scheduled by a given airline, which has already internalised its congestion externality. This implies that the congestion charging might favour the markedly already strong airlines and disfavour the airlines endeavouring to strengthen their market position (by more additional flights) or the new entrants (without the flights at all). This looks like a protection of the already gained rights - monopolies and oligopolies.

### *4.4.3 Estimating profitability of an additional flight*

The congestion charge should also be able to compromise the expected profitability of additional flights. If $C^{i}_{m,k+1}$ is the charge and $c^{i}_{k+1}(n)$ is the average cost per unit of time of an additional flight of capacity *(n)* of airline *(i)* (in the monetary units per unit of time) in *(k+1)*-th increment *Δt*, the total cost of this flight will be estimated as follows:

$$C^i_{f,k+1} = c^i_{k+1}(n) * \left[t^i_{f,k+1} + d_{k+1}\right] + C^i_{m,k+1} \tag{7}$$

where

$t^i_{f,k+1}$ is the duration of the additional flight of airline *(i)* scheduled in *(k+1)*st increment *Δt*

Other symbols are analogous to those in the previous expressions.
The expected revenues from the additional flight can be estimated as follows:

$$R^i_{f,k+1} = p^i_{k+1}(L) * \lambda^i_{k+1}\left[p^i_{k+1}(L)\right] * n^i_{k+1} \tag{8}$$

where

| | |
|---|---|
| $p^i_{k+1}(L)$ | is the average airfare per passenger of the additional flight on a route of length *(L)* scheduled by airline *(i)* in *(k+1)*st increment *Δt*; |
| $\lambda^i_{k+1}[p^i_{k+1}(L)]$ | is the expected load factor of the additional flight carried out by airline *(i)* in *(k+1)*st increment *Δt* assumed to be dependent on price; |
| $n^i_{k+1}$ | is the seat capacity of the new flight of airline *(i)* in *(k+1)*st increment *Δt*. |

This new flight will be unprofitable, if the following condition is fulfilled:

$$\Pi^i_{f,k+1} = R^i_{f,k+1} - C^i_{f,k+1} = p^i_{k+1}(L) * \lambda^i_{k+1}\left[p^i_{k+1}(L)\right] * n^i_{k+1} - c^i_{k+1}(n) * \left[t^i_{f,k+1} + d_{k+1}\right] - C^i_{m,k+1} \le 0 \tag{9}$$

where all symbols are as in the previous expressions.
To achieve the above condition, the charge $C^i_{m,k+1}$ should be slightly greater than the maximum value between the expected profits per flight and the cost of marginal delay, other factors constant. In such case, the airline will try to compensate the charge by increasing airfares. However, as can be intuitively concluded, the proportion of increase in the airfare will be higher at the smaller-cheaper flights, which impose the marginal delay cost on the greater number of the more expensive succeeding flights, than otherwise. In practice, this means that the small regional planes intending to operate at the congested airport(s) in the morning peak(s) will be penalised more. Consequently, in the case of elastic demand, increasing of airfares will force some passengers to give up, which will additionally deepen the losses and finally discourage the airline to launch the additional flight(s) at the intended time.

## 5 AN APPLICATION OF THE MODEL

The proposed model of the congestion charge is demonstrated on the case of New York (NY) LaGuardia airport under an assumption that the airport is not slot-controlled. This is one among three biggest airports serving the New York area (U.S.). In terms of the type of traffic, three airports mainly co-operate among each other. LaGuardia airport mainly serves the U.S. domestic short- and medium-"haul traffic. About 92% of flights are the origin-destination flights carrying about 45-55% business passengers. One of the reasons is closeness of the airport to the New York centre Manhattan, about 18km. After September 11/2001 terrorist attack and a sharp decline just afterwards, the traffic has gradually recovered and reached the annual number of about 22 million passengers and 358 thousands of flights by the end of the year 2002. The average number of passengers per flight has been always relatively stable during the past five years (58-62) (PANYNJ, 2003).

At present, 20 airlines operate at the airport. Three have the greatest market share in terms of the number of flights and the number of passengers, respectively: US Airways (38%; 14.2%), Delta (18%; 17.2%), and American (17%; 18.5%). Two right angle-crossing runways, each of length of 7000ft (2135 m), mostly influence the airline fleet structure in terms of the aircraft size and length of routes-markets they serve. The fleet mostly consists of the aircraft categories B737/717, A320 (100-150 seats), and the smaller regional jets and turboprops (70-110 seats). The average route length is 1200 km (Backer, 2000; PANYNJ, 2003).

The current runway capacity is about 80 (40/40) flights per hour under VMC (Visual Meteorological Conditions) and 64 (32/32) under IMC (Instrumental Meteorological Conditions) rules. These flights are accommodated at 60 parking stands at the apron.

The hourly and daily demand in terms of the number of flights frequently exceeds the capacity of runway and apron system, which causes severe congestion and delays. Since there is not available land for the further physical expansion, the options for relieving the expected flight congestion and delays under conditions of growth (19% until the year 2010 compared to the year 2002) appear to be very limited. The possible options actually consist of increasing of the average aircraft size on the one hand and rising of the runway capacity by introducing innovative operational procedures and technologies on the other. The former has already taken place by introducing B767-400ER (about 280 seats) in the year 2001 (AIRWISE NEWS, 2001). The later still have to take place. It is expected to increase the runway capacity for about 10% under VMC and about 3% under IMC rules (Federal Aviation Administration, 2003a). Nevertheless, both options seem not to be able to efficiently cope with expected congestion beyond the year 2010. This may again initiate thinking about implementing the economic measures of demand management. For example, the auction of slots (i.e., 'slottery') implemented in the year 2000 has substantially relieved congestion at that time. For the future, congestion charging might be reconsidered. At present, the airport landing charging is based on the aircraft weight. The unit charge is $6.55 for each five hundreds kilograms (thousand pounds) of the aircraft maximum take-off weight. In addition, each operation (flight) between 8:00 a.m. and 9:00 p.m. is charged by the fixed amount of US$100 (PANYNJ, 2003a).

## 5.1 Description of inputs

Three groups of inputs are used in application of the proposed model: data on the demand and capacity, for estimation of congestion and delays under given circumstances, and the aircraft operating costs and airfares, for assessing profitability of the particular flights.

### *5.1.1 Data for estimating congestion and delays*

The hourly rate of flight demand and corresponding capacity at NY La Guardia airport for every day in July 2001 have been used for estimating congestion and delays. The distributions of the hourly flight demand and their service rate (i.e., the airport capacity) have been designed, each based on 31 daily realisations (Federal Aviation Administration, 2003; 2003a). Each distribution for each hour has been assumed to be normal or nearly normal and independent on the others.

As well, the pairs of these distributions for different hours have also been assumed independent (Newell, 1982). Table 2 gives the main parameters of these hourly distributions.

In addition, in all experiments, the constant $C$ has been equal to 1.96 implying that the queues have stayed within the given confidence boundaries with the probability of 95% (Newell, 1982).

**Table 2** The main parameters of distributions of the flight inter-arrival and inter-departure time in given example

| **Time of the day** | **Demand Flight inter-arrival time** | | **Capacity Flight service time** | |
|---|---|---|---|---|
| Hour ($k$) | Mean ($t_{a,k}$) (s/flight) | St. dev.($\sigma_{a,k}$) (s/flight) | Mean ($t_{d,k}$) (s/flight) | St. dev.($\sigma_{d,k}$) (s/flight) |
| 1 | - | - | - | - |
| 2 | - | - | - | - |
| 3 | - | - | - | - |
| 4 | - | - | - | - |
| 5 | - | - | - | - |
| 6 | 90.72 | 9.972 | 52.56 | 7.488 |
| 7 | 52.20 | 3.942 | 52.92 | 7.524 |
| 8 | 50.76 | 3.123 | 52.2 | 4.608 |
| 9 | 49.68 | 4.716 | 52.56 | 7.776 |
| 10 | 50.04 | 4.860 | 52.20 | 7.164 |
| 11 | 50.40 | 1.764 | 51.12 | 6.912 |
| 12 | 50.76 | 2.376 | 51.12 | 6.984 |
| 13 | 48.96 | 3.096 | 50.76 | 6.912 |
| 14 | 51.84 | 3.744 | 50.76 | 6.336 |
| 15 | 50.04 | 3.312 | 50.40 | 7.056 |
| 16 | 48.24 | 2.916 | 50.40 | 7.020 |
| 17 | 48.60 | 5.148 | 50.04 | 7.022 |
| 18 | 51.48 | 8.640 | 50.04 | 7.020 |
| 19 | 50.76 | 5.292 | 50.40 | 7.704 |
| 20 | 51.84 | 7.992 | 49.68 | 6.624 |
| 21 | 59.67 | 5.220 | 49.32 | 6.012 |
| 22 | 78.12 | 16.236 | 49.32 | 5.976 |
| 23 | 123.84 | 36.468 | 50.40 | 7.308 |
| 24 | - | - | - | - |

*s –seconds; Source: FA A, 2003*

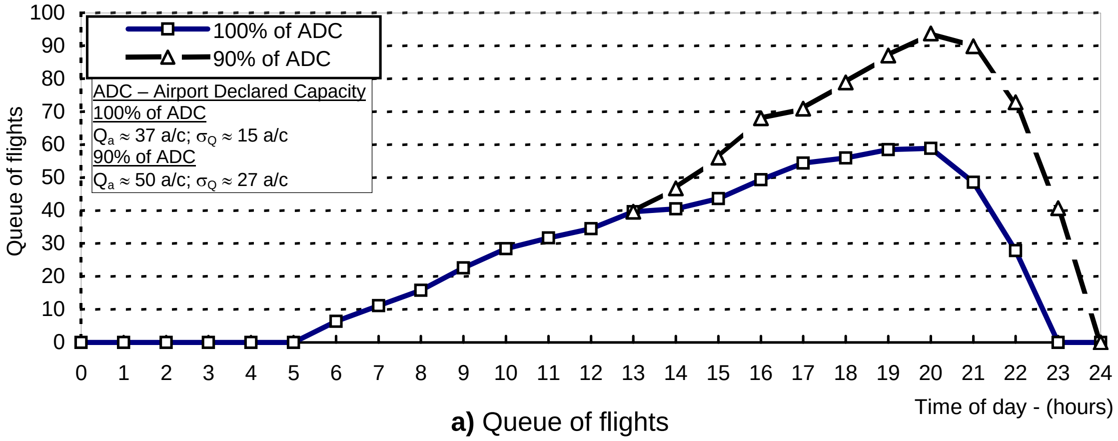
### *5.1.2 Aircraft operating costs and airfares*

The aircraft operating cost per block hour in dependence on the seat capacity has been estimated in the regression form using data on the U.S airlines as follows (FAA, 1998): $c(S) = 21.97\ S + 11.993\ (R^2 = 0.934; N = 45)$. According to this equation, the average cost of a flight of 100-150 seats (B737/717) operated at NY La Guardia airport varies between $US 2209 and $US 3307 per hour (or $US 37 and $US 55 per minute). The cost of a flight of 280 seats (for example B767-400ER), is $US 6162 per hour (or $US 103 per minute).

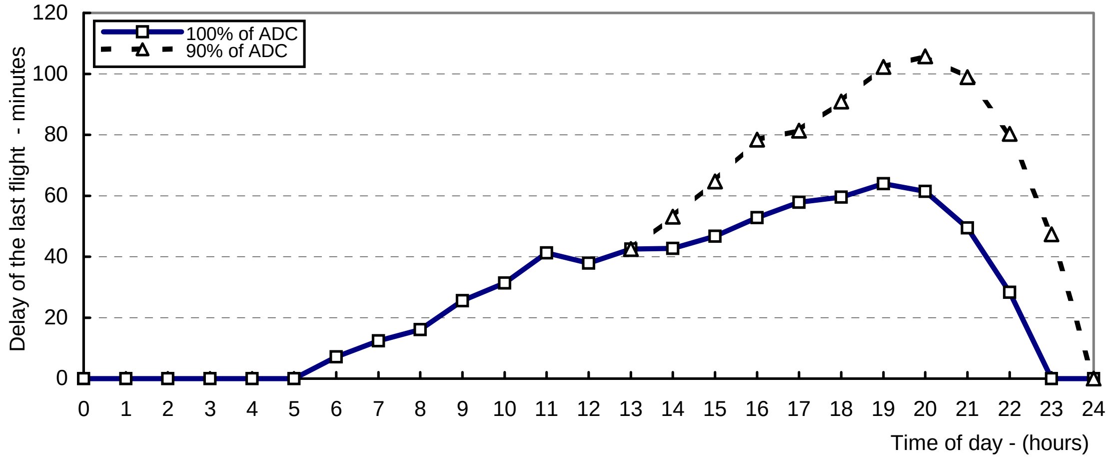
The average airfare per passenger at NY La Guardia airport in dependence on the non-stop flying distance has been determined by using the regression technique applied to the U.S. data from the year 1998 modified for changes in the value of $US for the year 2002 (Mendoza, 2002; Sheng-Chen, 2000) aqs follows: $p(L) = 9.5605\ L^{0.3903}\ (R^2 = 0.941; N = 28)$. For NY LaGuardia airport the average length of flight has been about 1200 km, which has given the average airfare of about $US 152 (Mendoza, 2002).

## 5.2 Analysis of the results

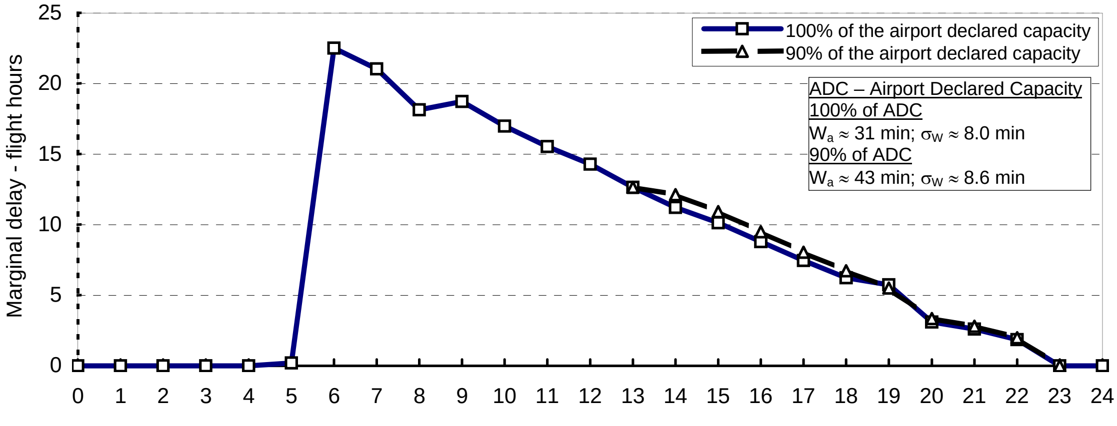
The results from the experiments with the model are shown in Figures 4, 4, and 6. Figure 4 (a, b, c) shows the congestion and delays of flights caused by an additional flight.



**a)** Queue of flights



**b)** Delay of the last flight in the queue



**c)** Marginal delay imposed by an additional flight

**Figure 4** The system congestion and delays in a given example

In Figure 4a, during an average day, the queue has started early in the morning just after opening the airport (06:00 hours), gradually increased afterwards, and reached the maximum between 19:00 and 20:00 hours. Then, during the next three hours (from 20:00 to 23:00 hours), the queue has been cleared. When the airport has operated at the declared capacity, the average queue has been 35 and the maximum queue 59 aircraft/flights. When the airport declared capacity has been diminished during the second half of the day (from 13:00 hours on, for example, for 10%, the queue has additionally increased, reached the maximum of 93 flights between 20:00 and 21:00 hours, and persisted until the midnight.

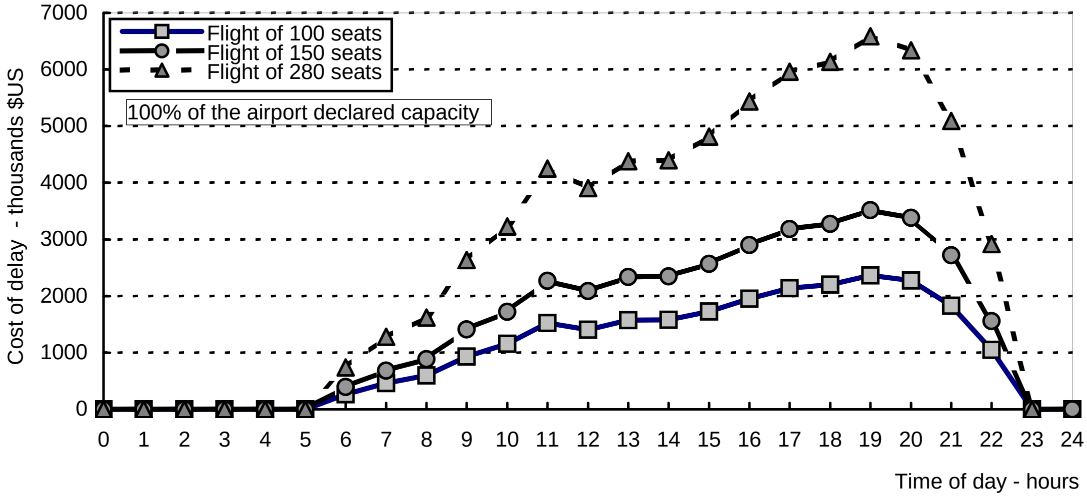
Figure 4b illustrates the flight delays as the consequence of queue. As can be seen, the delay of the last flight in the queue has changed in line with changing of the queue length. When the airport has operated at the declared capacity, the average and maximum delay per flight has been 35-40 and 65 minutes per flight, respectively. In the case of deterioration of the airport capacity for about 10%, from 13:00 hours on, the average and maximum delay per flight has increased to about 55-65 and 105 minutes, respectively.

Figure 4c illustrates changes of the marginal delay caused by changing of the scheduling time of an additional flight.. As can be seen, a flight scheduled early in the morning has imposed longer marginal delay then otherwise. In the given example, one such flight scheduled at 06:00 hours has imposed about 22 additional flight-hours of delay on the succeeding flights scheduled by the end of the congestion period. Scheduling of the new flight later during the day has affected the smaller number of succeeding flights and consequently caused less additional delays, as it has been intuitively expected. The average marginal delay imposed by an additional flight at any time during the day has been about 10-12 flight-hours. Deterioration of the airport declared capacity for 10% has increased this and the flight private delay. Figure 4b and 4c show that the marginal delay imposed on others has been considerably greater than the flight private delay.

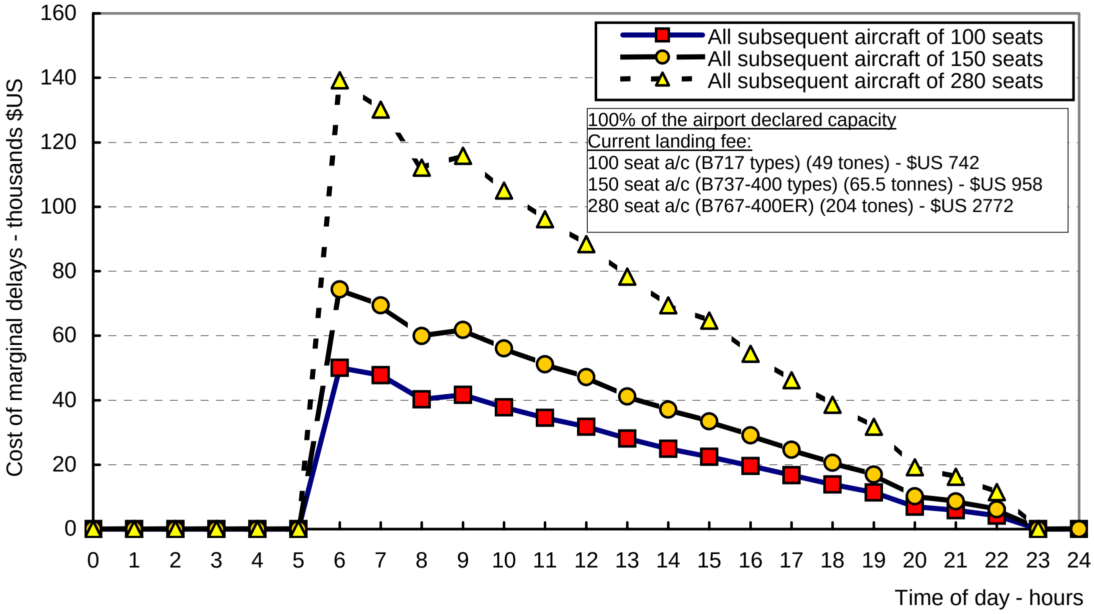
Figure 5 (a and b) shows the costs of an additional flight in the given example. Figure 5a shows the cost of delay of an additional flight in dependence on the time of day and aircraft size. As can be seen, this cost has generally increased with increasing of the aircraft size due to its higher operating costs. For given aircraft size, this cost has been proportionally increased with delays. For example, for an additional flight of capacity of 100, 150 and 280 seats scheduled between 19:00 and 20:00 hours, the cost of delay has been $US6500, $US3500 and $US2300, respectively.

Figure 5b shows that the costs of marginal delay imposed by an additional flight on the succeeding flights have changed in proportion to the marginal delays. They have been the highest when the additional flight has been scheduled early in the morning and gradually decreased if this flight has been scheduled later during the day. As well, these costs have been dependent on the aircraft (flight) types behind the additional flight, and vice versa. As has been expected, these costs have been higher if greater aircraft have been behind the additional flight. For example, the additional flight scheduled around 06:00 has generated the marginal cost of about $US50, $US75 and $US150 thousands, when all flights behind him have been carried out by the aircraft capacity of 100, 150 and 280 seats, respectively. Comparison of these marginal delay costs and current landing fees based on the aircraft weight have indicated existence of the large disproportion.

By summing up the costs of delays in Figure 5a and 5b, the costs of the total system delays caused by an additional flight have been obtained and the profitability of the additional flight estimated.



**a)** Cost of delay of an additional flight



**b)** Cost of the marginal delays imposed by an additional flight

**Figure 5** The system cost imposed by an additional flight in given example

Figure 6 shows conditions of such profitability in the given example. The additional flight of 2 hours has been carried out by an aircraft of 150 seats with the operational cost of $US3300, the average load factor of 60%, the average airfare of $US152 and consequently the revenue of $US13680. As has been operated by an airline as the new entrant (i.e., without market share), and fully charged by the congestion charge, this flight has been highly unprofitable during the whole day, except sometimes after 22:30 hours. Obviously, such entry would not be feasible under the conditions when all succeeding flights have been of 100 seats. However, when the given airline has already had significant market share in terms of the number of flights at the airport (85-90%), the additional flight has been profitable independently on the time when it has been scheduled.

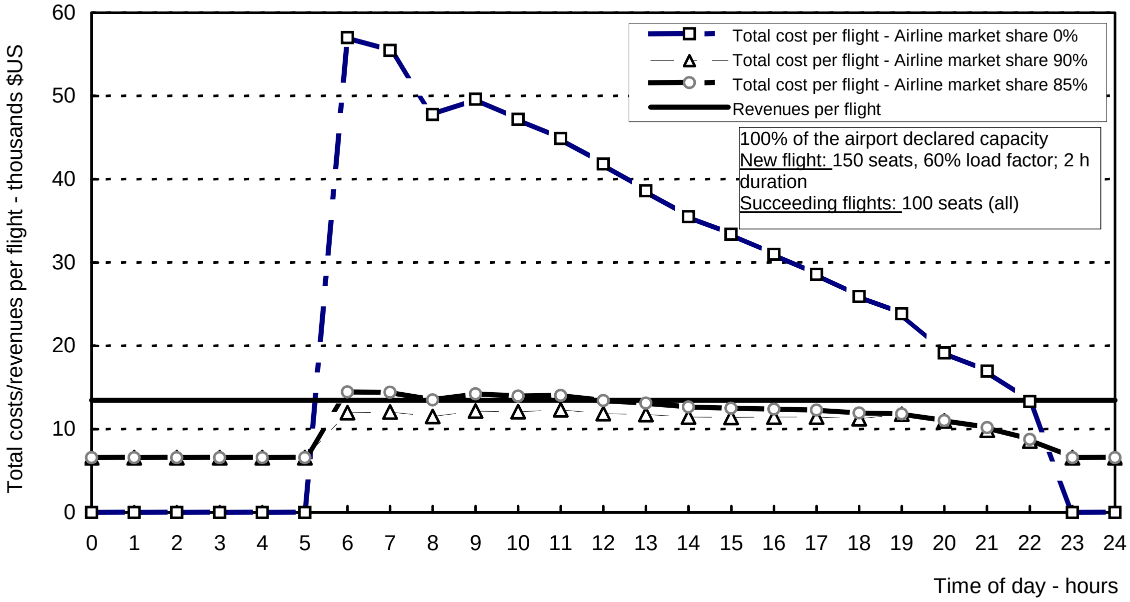


**Figure 6** Conditions of profitability of an additional flight in a given example

and despite been fully charged. In Figure 8, under given circumstances, the airline should have at least about 85% of market share (and thus the equivalent percent of its non congestion-charged flights) in order to have an additional flight profitable. As can be seen, this flight would be at the edge of profitability if being scheduled until early afternoon and absolutely profitable if being scheduled later. Under given circumstances, by increasing of the airline market share above 85%, the additional flight would be profitable independently on the time during the day. This result confirms doubts that the congestion charging might disfavour development of competition at the airport since it may impose unacceptably high congestion charges on flights of the new entrants on the one hand, and the very modest charges on flights of the airlines already being strongly present at the airport on the other. However, the congestion charging might stimulate flights to be carried out by the larger aircraft if being scheduled before the flights carried out by the smaller aircraft, and vice versa. As well, under given conditions, the charge might discourage the new flights during the first half of day, and particularly early in the morning.

## 6 CONCLUSIONS

The paper has developed the model for charging congestion at an airport. Currently, congestion charging is not practised at airports despite introducing different charging mechanisms for peaks and off-peaks. In addition to an analysis and comparison of airport delays in Europe and the U.S., different conditions influencing airport congestion have been examined. It has been emphasised that understanding the nature of congestion, reliable and transparent estimation of relevant parameters have been essential for developing the models and the system of congestion charging.

The model has consisted of the sub-models: diffusion approximation of queues to quantify the relevant queues and delays during congestion period; the model of marginal delays and their costs imposed by each flight on other flights during the congestion period; and the model of profitability of each flight burdened by the congestion charge. The modes have been applied to New York (NY) LaGuardia airport (U.S.) assumed to have the demand-free access.

The application has indicated that the model could efficiently deal with the problem of charging congestion at airports. In particular, the diffusion approximation of queues has enabled quantification of flight queues and delays realistically. Other two sub-models have estimated the congestion charge and profitability of particular flight(s) for the given traffic (congestion) scenario and charging conditions.

The results from the model have shown that the congestion charge at an airport could be used as the economic instrument of demand-management under following conditions:

Congestion as an exclusive consequence of the relationships between demand and airport capacity should cause delays longer than the threshold of fifteen minutes, i.e., when the demand/capacity ratio moves closer or exceeds one.

Congestion should be created by many flights of different competing airlines in order to raise the need for internalising the marginal costs of delays these flights impose on each other since a single airline with many flights has already internalised costs of marginal delays of these flights. In such context, the airports with many competing airlines performing point-to-point operations are more likely candidates for congestion charges than the airports with a few airlines operating hub-and-spoke networks despite in both cases the congestion can be significant and relevant for charging.

Congestion charge appears to be more effective in preventing access earlier during the congestion period of flights carried out by smaller aircraft before the flights carried out by the larger aircraft, and vice versa. This implies that the congestion charge stimulates exclusion of the earlier arrivals by the smaller-regional aircraft and favourites the use of the larger aircraft, which are less sensitive to the time of arrival.

Congestion charge appears to stimulate additional flights of airlines with significant airport market share, i.e., those with more flights with already internalised cost of marginal delays. In such sense, it contributes to consolidation of the market position of the incumbents, discourages new entries and thus compromises competition at the airport during the congested period.

## 7 REFERENCES

ACI, (2002), **Airport Charges in Europe**, Report of Airport Council International (Europe), p. 39

Adler, N., (2002), “Barriers and implementation Paths to Marginal Cost Based Pricing: Rail, Air and Water Transport”, **3rd MC-ICAM Seminar**, 2/3 Sept., p.5

AEA, (2001), **Yearbook 2000,** Association of European Airlines, Brussels, Belgium, p.80

AIRWISE NEWS, (2001), “Delta Launches Boeing 767-400ER At La Guardia”, **http://news.aiwise.com**

ATA, (2002), **System Capacity: Part I: Airline Schedule, Airport Capacity, and Weather**, Air Transport Association, Industry Information, USA, http://www.air-transport.org/public/industry

Backer, C., (2000), “Airports: Top 1000 Ranking”, **Airline Business**, pp. 55-86

Brueckner, J. K., (2002), "Internalisation of Airport Congestion", **Journal of Air Transport Management**, Vol. 8, pp. 141-147

BTS, (2001), **Airline Service Quality Performance Data**, US Department of Transportation, Bureau of Transportation Statistics, Office of Airline Information, Washington DC, USA

Carlson, F., "Airport Marginal Cost Pricing: Discussion and an Application to Swedish airports", **Discussion Paper**, Department of Economics, Göteborg University, Sweden, p. 20

Cheng-Shen, A. H., (2000), "An Analysis of Air Passenger Average Trip Lengths and Fare Levels in US Domestic Markets", **Working Paper UCB-ITS-WP-2000-1**, NEXTOR Aviation Operations Research, Institute of Transport Studies, University of California, Berkeley, USA, p. 14

Corbett, J. J., (2002), "Small Communities Are Concerned about Congestion Pricing", **The Air and Space Lawyer**, Vol. 17, No. 1, Summer, pp. 17-21

Daniel, J. I., (1995), "Congestion Pricing and Capacity of Large-Hub Airports: A Bottleneck Model with Stochastic Queues", **Econometrica**, Vol. 63, pp. 327-370

Daniel, J. I., Pahwa, M, (2000), "Comparison of Three Empirical Models of Airport Congestion Pricing", **Journal of Urban Economics**, Vol. 47, pp. 1-38

Daniel, J. I., (2001), "Distributional Consequences of Airport Congestion Pricing", **Journal of Urban Economics**, Vol. 50, pp. 230-258

DeCota W., (2001), "Matching Capacity & Demand at LaGuardia Airport", NEXTOR, Airline & National Strategies for Dealing with Airport & Airspace Congestion, p. 26

Doganis, R, (1992), **The Airport Business**, Routledge, London, UK

EC, (1997), **External Cost of Transport in ExternE**, European Commission, Non Nuclear Energy Programme, IER Germany, Germany

EC, (2001), **Concerted Action on Transport Pricing Research Integration – CAPRI**, Final Report, European Commission, Transport RTD of the 4th Framework Programme, ST-97-CA-2064, Brussels, Belgium

ECMT, (1998), **Efficient Transport for Europe: Policies for Internalization of External Costs**, European Conference of Ministers of Transport, OECD-Organisation of Economic Co-operation and Development, Paris, France

EUROCONTROL, (2002), **An Assessment of Air Traffic Management in Europe During Calendar Year 2001: Performance Review Report**, Performance Review Commission, EUROCONTROL, Brussels, Belgium

EUROCONTROL/ECAC, (2001), **ATFM Delays to Air Transport in Europe**, Annual Report 2000, CODA, EUROCONTROL, Brussels, Belgium

EUROCONTROL/ECAC, (2002a), **ATFM Delays to Air Transport in Europe: Annual Report 2001**, EUROCONTROL, Brussels, Belgium

FAA, (1998), **Economic Values for Evaluation of Federal Aviation Administration Investment and Regulatory Decisions**, Report FAA-APQ-98-8, Federal Aviation Administration US Department of Transportation, , Washington DC, USA

FAA, (2003), **Airport Capacity Benchmarking Report 2001**, Federal Aviation Administration, Washington D.C., USA,

FAA, (2003a), **Aviation Policy and Plans (APO) – FAA OPSNET and ASPM**, Federal Aviation Administration, Washington D.C., USA

Fron, X., (2001), “Dealing with Airport and airspace Congestion in Europe”, **ATM Performance**, the paper presentation, Brussels, EUROCONTROL meeting, March, p. 25

Ghali, M. O., Smith, M. J., (1995), “A Model for the Dynamic System Optimum Traffic Assignment Problem”, **Transportation Research B**, Vol. 29B, pp. 155-170

Hall, R.W., (1991), **Queuing Methods for Services and Manufacturing**, Prentice Hall International Series, Prentice Hall International Limited, London, UK

Janic, M., (2003), “Large Scale Disruption of An Airline Network: A Model for Assessment of the Economic Consequences”, **The 81st Transportation Research Board (TRB) Conference**, January, Washington DC, USA

Liang, D., Marnane, W., Bradford, S., (2000), “Comparison of US and European Airports and Airspace to Support Concept Validation”, **3rd USA/Europe Air Traffic Management R&D Seminar**, Napoli, 13/16 June, p. 15

Mendoza, G., (2002), **New York State Airport Air Fare Analysis**, Aviation Service Bureau, NYSDOT, Washington DC, USA, p. 4

Nash, C, Sansom, T., (2001), “Pricing European Transport System: Recent Developments and Evidence from Case Studies”, **Journal of Transport Economics and Policy**, Vol. 35, Part 3, pp. 363-380

Newell, G. F., (1979), “Airport Capacity and Delays”, **Transportation Science**, Vol. 13, No. 3, pp. 201-241

Odoni, A., Bowman, J., et al., (1997), **Existing and Required Modelling Capabilities for Evaluating ATM Systems and Concepts**, NASA/AATT Final Report, International Centre for Air Transportation, Massachusetts Institute of Technology, Massachusetts, USA, p. 206

Odoni, A. R., Fan, T. C. P., (2002), “The Potential of Demand Management as a Short-Term Means of Relieving Airport Congestion”, **4th USA/Europe Air Traffic Management R&D Seminar**, Santa Fe, 3-7 Dec., USA”, p. 11

PANYNJ, (2003), **La Guardia Airport: Traffic Statistics**, Report, The Port Authority of NY&PJ, New York, USA, p. 2

PANYNJ, (2003a), **Schedule of Charges for Air Terminals**, Report, The Port Authority of NY&PJ, New York, USA, p. 40

Schiphol Group, (2002), **Annual Report-2001**, Amsterdam Schiphol Airport, Amsterdam, The Netherlands

Vickery, W., 1969, "Congestion Theory and Transport Investment", **American Economic Review**, Vol. 59, No. 2, May, pp. 251-260

Welch, J.D., Lloyd, R.T., (2001), "Estimating Airport System Delay Performance", **4th USA/Europe Air Traffic Management R&D Seminar**, Santa Fe, 3-7 Dec., USA", p. 11