CONGESTION CHARGING AT AIRPORTS: DEALING WITH AN INHERENT COMPLEXITY

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ABSTRACT

This paper deals with modelling of congestion charging at airports. The congestion charging represents internalising of the system additional (marginal) delays imposed by an additional aircraft on the succeeding aircraft during congestion period. The existing concepts of the congestion charging are additionally concretised by taking into account the real-life congestion conditions and differences between the particular flights in terms of their scheduling time, type in terms of the seat capacity, operational cost, duration (short, medium, long-haul), the number of passengers on board, and revenues.
The queuing model based on a diffusion approximation is used to estimate the airport congestion and delay. Additional models are developed to estimate feasibility of the flight access to an airport with the internalised congestion. The numerical experiments with the model are carried out to illustrate an application of the proposed modelling procedure.

KEY WORDS: airport, congestion charging, modelling, queuing theory, diffusion approximation

1 INTRODUCTION

Air transport congestion has increased during the past decade both in Europe and U.S. The main reasons have been growing demand, constrained capacity of infrastructure, and disruptions of scheduled services (Janic, 2003). The congestion caused by the imbalance between demand and capacity has been remedied by the 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, the second option has been difficult or even impossible to be implemented in the short-term due to the various political and environmental constraints in terms of noise, air pollution and land use. The last, demand management has recently been considered as potentially viable option to relieve the congestion problem (Adler, 2001; DeCota, 2001; Federal Aviation Administration, 2001)

In addition to the institutional instruments, demand management at airports embraces the economic instruments such as congestion charging and auctions of slots. A central issue of the congesting charging relates to the estimation of marginal delay cost imposed by an additional flight to all other subsequent flights during congested period. In such a context, the additional flight has to pay its private cost of delay and a charge equivalent to the marginal cost of delays imposed on the subsequent flights during congestion period. This charge may increase the overall flight cost, and thus compromise its overall profitability. The current charging system at the European and U.S. airports is mainly based on the aircraft weights and has a little in common with the above concept of congestion charging (Airport Council International, 2001; Adler, 2002; Doganis, 1992).

This paper deals with modelling of the congestion charging 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 the European and U.S airports. Section 3 elaborates the real-life conditions under which congestion charging could be implemented (i.e., internalised). Section 4 deals with modelling of congestion charging. Section 5 provides the numerical examples demonstrating usefulness of the modelling procedure. Section 5 contains some conclusions.

2 AIRPORT DEMAND, CAPACITY AND CONGESTION IN EUROPE AND UNITED STATES

Dealing with congestion charging at airports includes an analysis of the relevant parameters such as demand, capacity and congestion. Demand is represented by the flights scheduled at an airport, usually by one or more airlines. At many large European and U.S. (hub and non-hub) airports, the most numerous are the flights of one or few airlines, their subsidiaries and alliance partners. These flights use the available arrival and departure slots, i.e., the airport declared capacity[1], while getting in service at the airport.

2.1 Demand versus capacity

The number of flights at an airport is always balanced with the airport declared capacity aiming at preventing serious congestion. In Europe, the initial demand and available airport capacity are balanced through the multi-stage process of negotiations between airlines, airports and air traffic control. In such a context, the demand is generally not allowed to exceed the capacity for the long period of time, which, under the regular functioning, excludes serious congestion. Nevertheless, due to the system imperfectness and the other disrupting factors, the actual demand frequently exceeds the airport declared capacity and thus causes congestion and delays (EUROCONTROL, 2002, Janic, 2003).

In the U.S., the demand and capacity are balanced through the multistage process too. However, in this case, the initial demand driven by both the market forces and the airline scheduling practice is allowed to exceed the airport capacity frequently during the short periods of time. In such case, the consequent congestion and delays are assumed to be the planned categories (ATA, 2002, Liang et al., 2000). Also in this case, disrupting factors may affect the planned operations and thus unpredictably increase

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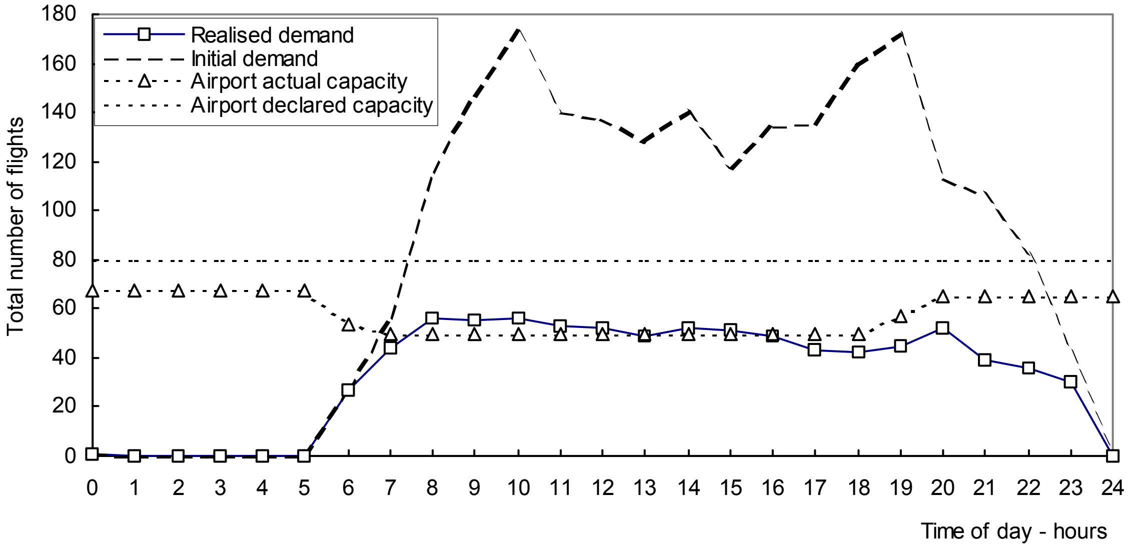
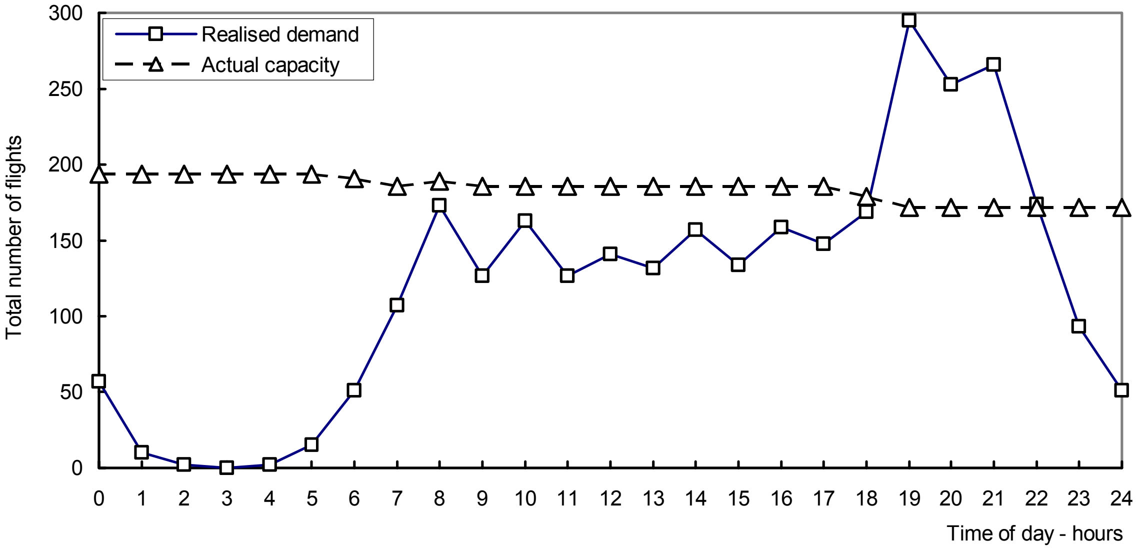
[1] In Europe, the number of arrival and departure flights accommodated at an airport during given period of time (usually one hour) under given conditions determines the airport declared capacity. This capacity is based on IMC (Instrumental Meteorological Conditions) and IFR (Instrumental Flight Rules). 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 'optimal' one determined for VMC

anticipated congestion and delays (Federal Aviation Administration, 2001, 2002a; Janic, 2003). Figure 1a illustrates an example of the two-stage balancing of the demand and



a) New York LaGuardia airport



b) Atlanta Hartsfield airport

Figure 1 The relationships between demand and capacity at U.S. airports (Compiled from Federal Aviation Administration, 2002a)

(Visual Meteorological Conditions) and VFR (Visual Flight Rules), and the 'reduced' one determined for IMC and IFR (Federal Aviation Administration, 2001).

capacity at New York LaGuardia airport (U.S) during one peak day, 30 June 2001 (beginning of the Independence Day holiday) (Federal Aviation Administration, 2002a). As can be seen, at the first stage the initial demand was much higher than the airport actual capacity (which was lower than the declared capacity). At the second stage, the demand was suppressed closer to the expected capacity but remained above the capacity during the morning.

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 demand pattern has been quite different than at LaGuardia airport illustrating the different – hub-and-spoke - pattern of the main incumbent (Delta Airlines). In the morning and afternoon hours the realised demand has been lower than the capacity, but it has considerable exceeded the capacity (which has also changed during the day) in the late afternoon and evening (18.00-22.00) hours.

2.2 Congestion and delays

Airport congestion causes delays of flights. In general, delay is defined as the difference between the actual and scheduled time of being at the 'referent location'. The threshold for either arrival or departure delayed flight is the period of 15 or more minutes behind the schedule (Association of European Airlines, 2001; Bureau of Transport Statistics, 2001; EUROCONTROL, 2001; Federal Aviation Administration, 2002a,).

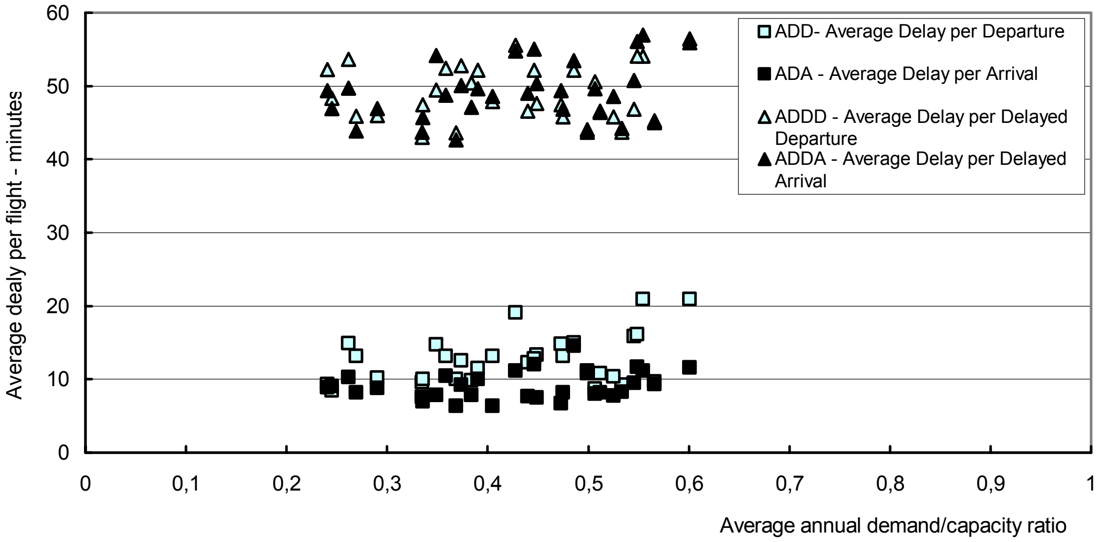
At the European and U.S. airports, the congestion and delays have become their common (and inherent) operational characteristic. Table 1 shows some relevant statistics. As can be seen, the proportion of delayed flights has been different in both regions. In Europe, this proportion has varied between 17% and 30% for arrivals, and 8% to 24% for departures. In the U.S., the 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 the European airports Delays at airports are generally expressed as the averages per any flight and the averages 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; Federal Aviation Administration, 2002a).

Table 1: Flight delays at congested European and U.S. airports

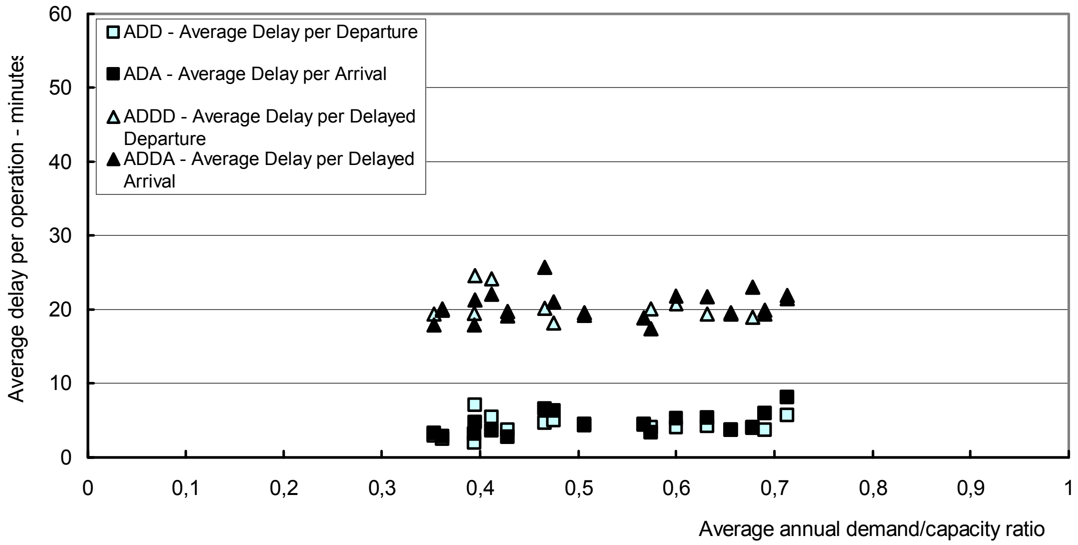
European airports ***(2001)***	***(%) of delayed flights***			***U.S. airports*** ***(1999)***	***(%) of delayed flights***	
	Arrivals	***Departures***			***Arrivals***	***Departures***
Paris CDG	24.6	21.8		Chicago-O'Hare	33.6	29.9
London Heathrow	17.4	21.0		Newark	38.4	31.0
Frankfurt	30.8	18.9		Atlanta	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; Federal Aviation Administration, 2002a

In addition, segregation of delays into the arrival and departure delays is often carried out. Figure 2 (a and b) shows both types of delays at 32 U.S. and 17 European most congested airports in dependence on the average annual demand/capacity ratio (i.e., utilisation of airport capacity).



a) U.S. Airports (Source: Federal Aviation Administration , 2002a)



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

Figure 2 Examples of the dependability between the average delay and average annual utilisation of the airport capacity

As can be seen, the average delay per flight – 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 latter between 5 and 15 minutes. At the European airports, there has not been obvious distinction between the average delay per an arrival and departure flight. Almost all delays have been shorter than 15 minutes. In both regions, the very slight increasing of delays for both operations in line with increasing of the demand/capacity ratio have been noticeable. According to the threshold of 15 minutes, the flights in both samples should not be considered delayed at all.

The picture changes when the delays per delayed flights are considered. In given sample, the average delay per delayed flight – arrival and departure - has again been longer at the U.S. than European airports, 40-60 minutes compared to 15–25 minutes, respectively. In both regions, these delays have been the similar for both types of flight operations and rather non-influenced by the airport demand/capacity ratio. According to the threshold of 15 minutes, these have been the really delayed flights, but caused by many causes. In the U.S., on average, bad weather has caused about 70-75% and congestion about 20-30% of these delays (Bureau of Transport Statistics, 2001; Federal Aviation Administration, 2001; 2002a). In Europe, on average, severe weather has caused only 1-4% and congestion about 30-40% of these delays (Association of European Airlines, 2001; EUROCONTROL, 2001).

Figure 2 (a and b) also shows that the average demand/capacity ratio, i.e., the utilisation of the airport capacity, has varied between 25% and 65%, and between 35% and 75 % at the U.S. and European airports, respectively. This indicates that, at almost all airports, at an average annual scale, the external factors influencing demand as well as the demand management have always kept the demand at the level lower than the capacity, as a rule for preventing the extreme congestion (Welch and Lloyd, 2001; Odoni and Fan, 2001).

3 CONGESTION CHARGING AT AIRPORTS

3.1 Background

Dynamic interaction of the demand and capacity cause congestion at airports. The rate of such interaction is commonly measured by ratio of the intensity of demand and capacity (or the capacity utilisation ratio), which generally may take the values lower, equal or greater than one. Specifically, if the intensity of demand is equal to the capacity, this ratio is equal to 1.0 (or 100%) (Newell, 1982). At the most European and U.S congested airports, contrary to the above-mentioned averages, this ratio often reaches or even exceeds the value 1.0 (100%), particularly during the short peak periods of an hour or quarter of hour, which suggests occurrence of the significant congestion and delays[2] (Federal Aviation Administration, 2001; 2002a). This gives rise to the question of managing this ratio and thus congestion below the threshold levels. In the short-term, this seems to be possible by the demand management, and particularly by using its economic instrument - congestion charging (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, congestion charging has still not found practical application at the congested airports. 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 intended 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 feasible long-term solution for relieving congestion despite the various short-term social, political and environmental barriers. Consequently, the very rare, if any, airports have considered congestion charging as the viable short-term remedy. At the same time, the revenues from combined aeronautical[3] and non-aeronautical charges have provided coverage of the airport operational costs and partly funding of investments.

3.2.2 Complexity of measurement of conditions

Many simultaneous causes have usually caused congestion, of which the demand/capacity ratio being around or greater than one during the peaks has been among the most important ones. These peaks have been different at different airports in terms of frequency and duration, type of operations, and type of aircraft involved.

In terms of the *frequency and duration*, the short and frequent peaks have been mostly created by the airline hub-and-spoke operations. The long and infrequent peaks have

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[2] 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).

[3] A part of the aeronautical charges has consisted of landing fees based on the aircraft weight (Airport Council International, 2001).

been created due to large demand, which has exceeded capacity for several hours during the day.

In terms of *the type of operation and aircraft types*, congestion during the peaks have affected both arrival and departure flights and sometimes transferred delays between them. These flights have been carried out by the same or different aircraft types of either co-operated or competed airlines. In addition, the materialised congestion has often been additionally affected by other causes, which has made extraction of the relevant causes for the purpose of the congestion charging complex or even impossible. In addition, there has been the lack of criteria for setting up the relevant level of congestion to be internalised. Since congestion caused 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). In addition, internalising of congestion due to 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 schedules, and thus force the affected airlines to leave the airport. In the latter 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

Congestion charging at airports seems to be itself ambiguous. Actually, it is supposed to impose a charge on an additional flight equivalent to the cost of marginal delay cost, which this flight imposes on the succeeding flights during congestion period. The objective is to deter (i.e., prevent) appearance of such flight (and to divert all other flights, which create congestion), which seems to be in collision with the guaranteed freedoms of the unlimited access to 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 strong to unwillingly suppress the elastic demand. As well, internalising and relations between this and the other airport externalities (burdens) such as noise or air pollution, as well as the relations of these with existing charging schemes based on the aircraft take-off weight are not quite clear and transparent. Furthermore, there may be a problem of spending the collected charges. If they would be used for increasing of the airport capacity by expansion of infrastructure, the source of revenues – congestion – would vanish afterwards for a while. It is less likely to consider allocation of this money outside the industry. Last but not least, it seems difficult and sensitive to impose the additional charges to the economically and financially vulnerable airline industry.

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

- Institutional, organisational, political and legal barriers maintained by the monopolistic powerful hub airports (Europe) and powerful airlines (both in Europe and U.S.) including 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
- Technological barriers in collection of the relevant data on the actual causes of congestion at airports including the precise data on the airport capacity (Europe). Relatively useful databases already exist in the U.S. (FAA, 2002a).

4 MODELLING CONGESTION CHARGING AT AN AIRPORT

4.1 The previous research

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 costs that it imposed on all other subsequent flights during congestion. In the nineties, this marginal delay cost has been considered as the externality to be internalised together with some other externalities such as air pollution, noise and air traffic accidents (Adler, 2002; Brueckner, 2002; Daniel, 1995; Daniel and Pahwa, 2000; Daniel, 2001; EC, 1997; European Conference of Ministers of Transport, 1998; Odoni and Fan, 2001; Vickery, 1969). In such a 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 the peaks by congestion charging was suggested since the airport airlines and passenger already found a balance of their interests within given circumstances (Daniel, 1995; Daniel, 2001). Comparison of different models of the airport congestion charging produced some interesting results on the models' performance, but again failed to properly address the reasons for suppressing the peaks already agreed by the particular actors involved by congestion charging (Daniel and Pahwa, 2000). In addition, some research also tackled the problem of congestion charging at airports where the airlines might have different market dominance, under an assumption that they had already internalised their congestion cost (Bruckener, 2002).

Despite being theoretically sophisticated and advanced, almost all above (economic) models suffered from a lack of sufficient reality, which was one of the reasons why they remained mostly within the academic domain. One of the factors making them too unrealistic, with partial exception of the work of Daniel (1995; 2001) and Brueckner (2001), related to the analogy between congested roads and airports, where the only similarity shown to be type of the 'predictable' queues (Hall, 1991). In addition, the models a priory assumed that congestion charging based on the marginal delay cost would be effective as expected. As well, some recent research has suggested implementation of the congestion charging (in addition to other externalities) non-selectively (for example, at all or almost all European airports), which could face the strong opposition of both the airports and airlines (Adler, 2002).

4.2 Assumptions

In this paper, modelling of the congestion charging at an airport as the continuation of previous research, is based on several assumptions. The time–varying demand and capacity profile at the candidate airport need to be known during typical (representative) day. The demand profile can be obtained from the published airport (and airline) schedule(s). In such a context, each flight (or a group of the similar flights) is considered with respect to the average operational cost and revenue. 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 the particular arriving and departing flights. The runway system is assumed to be a critical element of the airport congestion.

Only the long peaks in which the demand/capacity ratio is coming close to or exceeding 1.0 (100%) and thus cause severe congestion are considered for internalising. This assumption can be used for selection of the candidate airports, which has not been the case in some previous studies (Adler, 2002).

The number of flights during such peaks is assumed to be large (at least several dozens), which makes congestion mainly dependent on the predictable variations (and positive differences) between demand and capacity[4]. This makes application of the queuing model based on the diffusion approximation 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

Congestion charging at an airport requires estimation of the system marginal delay, which consists of the sum of i) the private cost of delay of the additional flight, and ii) the cost of marginal (additional) delay, which this flight imposes on the succeeding flights during the congested period (Ghali and Smith, 1995; Hall, 1991). These delays can be estimated by using the various queuing models and simulation developed up to date (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 an airport, at time (t), $\rho(t) = \lambda(t)/\mu(t)$ where $\lambda(t)$ is the flight arrival rate (i.e., the demand for service) and $\mu(t)$ is the capacity (i.e., the flight service rate). Different techniques are developed to estimate congestion and related delays in dependence on $\rho(t)$. One of them, a graphical

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[4] 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).

representation of the typical queuing process at the congested facility (an airport) during period *T* (one day) is shown in Figure 3.

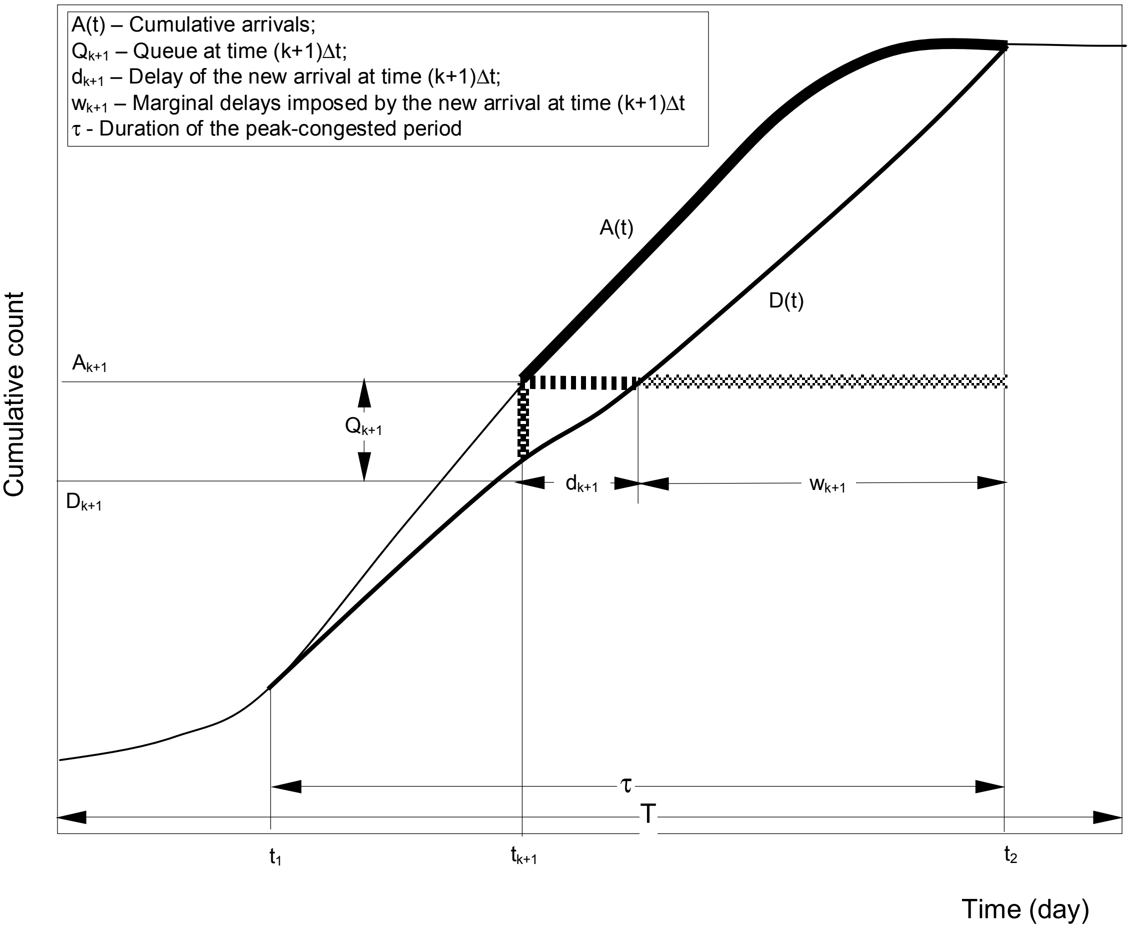

Figure 3 A scheme of a typical queuing process at the congested airport – the cumulative count of flights

The *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 being 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 $(0, t_1)$, the *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 $(t_1, t_2) \equiv \tau$, the $A(t)$ 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) the $A(t)$ again drops bellow $D(t)$ and the similar developments as in the first sub-period take place. Obviously, only the congestion during the period (τ) should be considered to be internalised since it is certainly able to produce the delays longer than the threshold of 15 minutes (Hall, 1991; Newell, 1982). To estimate these congestion and delays, let period (τ) be divided into K equal increments Δt (i.e., $K * \Delta t \approx \tau$). Each increment Δt should be sufficiently short[5] in comparison to the period (τ) in order to register the changes of 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 Δt, $A(k+1) - A(k) \equiv A_{k+1} - A_k$ 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 Δt, will also be the stochastic variable with normal probability distribution $(k \in K)$ (Newell, 1982). Consequently, the flight queue in $(k+1)$st interval Δt, can be approximated as follows:

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

where

Q_k is the queue in (k)th increment Δt;

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[5] For example, if (τ) is the period of several hours during the day, Δt will certainly be quarter, half or an hour.

$\overline{Q}_k, \overline{Q}_{k+1}$ is the average queue in (k)th and $(k+1)$st increment Δt, respectively;

λ_{k+1} is the intensity of flight demand in $(k+1)st$ increment Δt;

μ_{k+1} is the airport capacity (i.e., the flight service rate) during $(k+1)st$ increment Δt;

B_{k+1} is the anticipated deviation of the actual flight queue (i.e., a “buffer”) from its average in $(k+1)st$ increment Δt.

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):

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

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 Δt;

$\sigma_{a,k+1}; \sigma_{d,k+1}$ is the standard deviation of the flight inter-arrival and service time, respectively, in $(k+1)$st increment Δt;

C is constant ($C = \Phi^{-1}(1-p)$, where Φ^{-1} is the inverse Laplace’s function and p is the probability that the flight queue in $(k+1)$st increment Δt 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 Δt

(Newell, 1982):

In expression (1) and Figure 3, at the beginning of period *(τ)*, 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 joins the queue already built up due to the previously dominating ‘random effects’. The latter queue $\overline{Q}_0$ can be approximated as follows (Newell, 1982):

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

where

m is the index of time increment Δt 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 their costs

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

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

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:

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

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

As can be seen 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 certainly increases the marginal delays. As well, if the additional flight is scheduled closer to the beginning of the peak, the marginal delays will be 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:

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

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 new 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 the new 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 The profitability of an additional flight

The congestion charge should also be able to compromise the expected profitability of the 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 new 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 new flight of route 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 new 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:

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

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 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 new flight at the intended time.

5 NUMERICAL APPLICATION

The proposed modelling procedure of the congestion charging is demonstrated on the case of New York (NY) LaGuardia airport. 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-distance 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 of which three have the greatest market share in terms of the number of flights and 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 determine 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 seat) as well as of some smaller regional jets and turboprops (70-110 seats). The average route length is 1200 km (%) (Backer, 2000; Port Authority of New York & New Jersey, 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. The flights are accommodated at 60 apron parking stands.

The hourly and daily demand in terms of the number of flights frequently exceeds the capacity of both components, 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 latter, which still have to take place, is expected to increase the runway capacity for about 10% under VMC and 3% under IMC rules (Federal Aviation Administration, 2003a). Nevertheless, both options are not seemed to be able to efficiently cope with 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 (Port Authority of New York & New Jersey, 2003a).

5.1 Description of inputs

Three groups of inputs are used in application of the proposed modelling procedure: 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 rates of the number of flights demanding service and their 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, which has implied that the queues have stayed within the given confidence boundaries with 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: Federal Aviation Administration, 2003

5.1.2 Aircraft operating costs

The aircraft operating cost have been expressed per block hour, in dependence on the seat capacity. The data related to the U.S airlines are given in Figure 4 (Federal Aviation Administration, 1998). As can be seen, this cost increases with increasing of the aircraft seat capacity (size). According to given regression 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 flight of 280 seats (for example B767-400ER), is $US 6162 per hour (or $US 103 per minute).

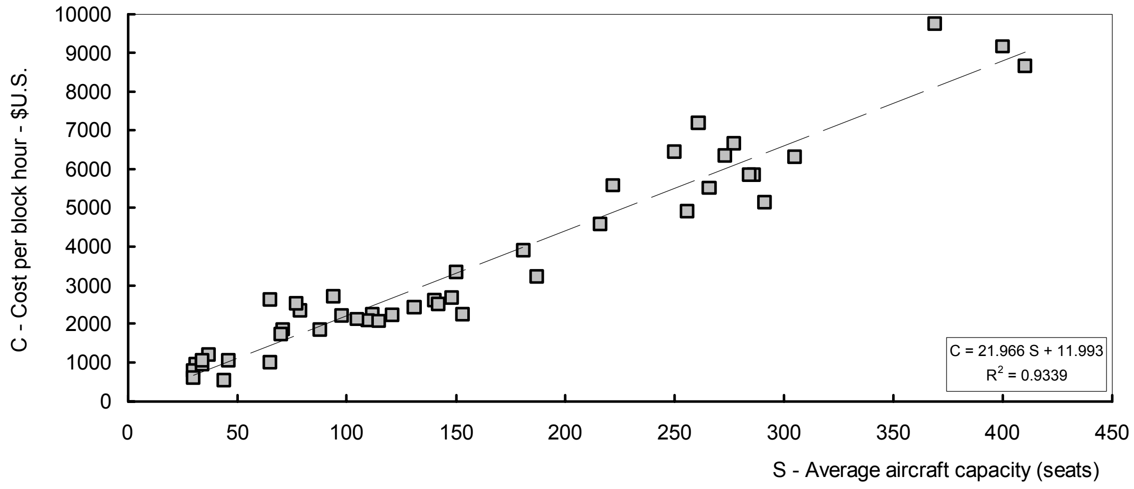


Figure 4 Dependence of the flight operating cost on aircraft seat capacity (Compiled from Federal Aviation Administration, 1998)

5.1.3 The airfares

The average airfare per passenger at NY La Guardia airport has been determined by using the U.S. data from the year 1998, but modified for changes in the value of $US for the year 2002 (Mendoza, 2002; Sheng-Chen, 2000). Figure 5 illustrates dependence of airfare on the route length.

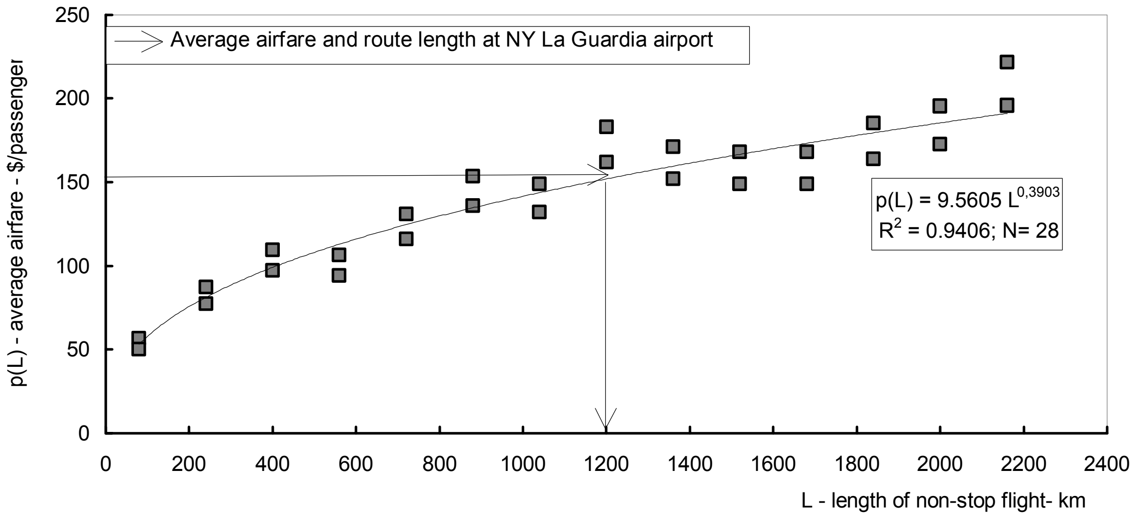
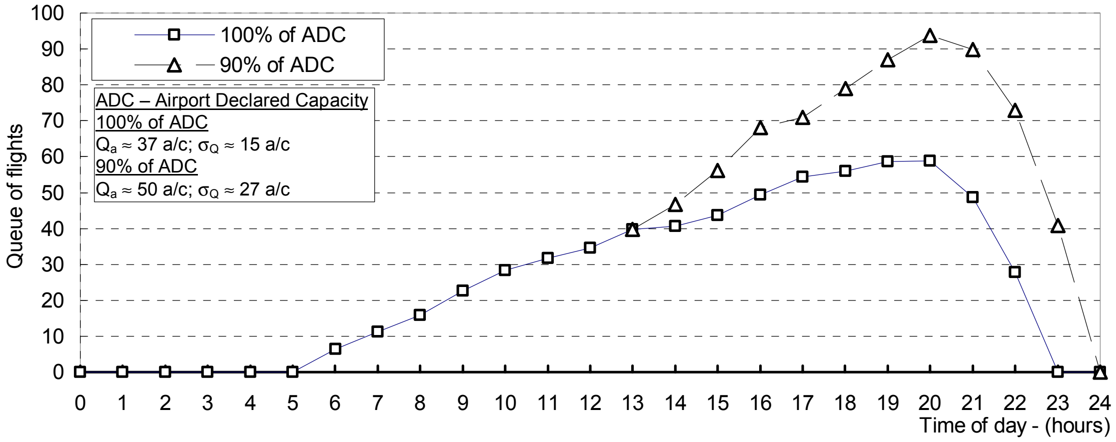


Figure 5 Dependence of the average airfare on length of the non-stop flight (Compiled from Sheng-Chen, 2000; Mendoza, 2002)

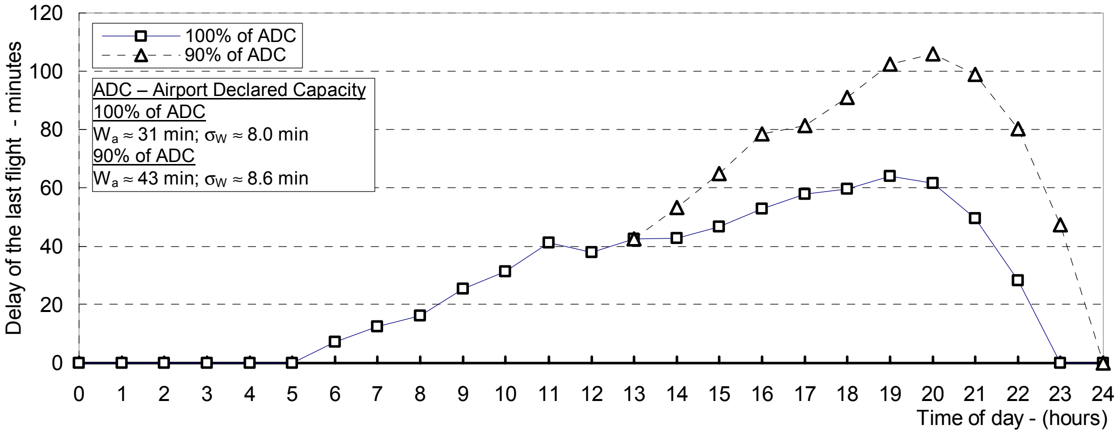
As can bee seen, the average airfare per passenger has increased at decreasing rate with increasing of route length, which can be explained by the fact that the airfares have reflected changing of the average unit cost per flight with the flying distance (Janic, 2001). For NY LaGuardia airport the average 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

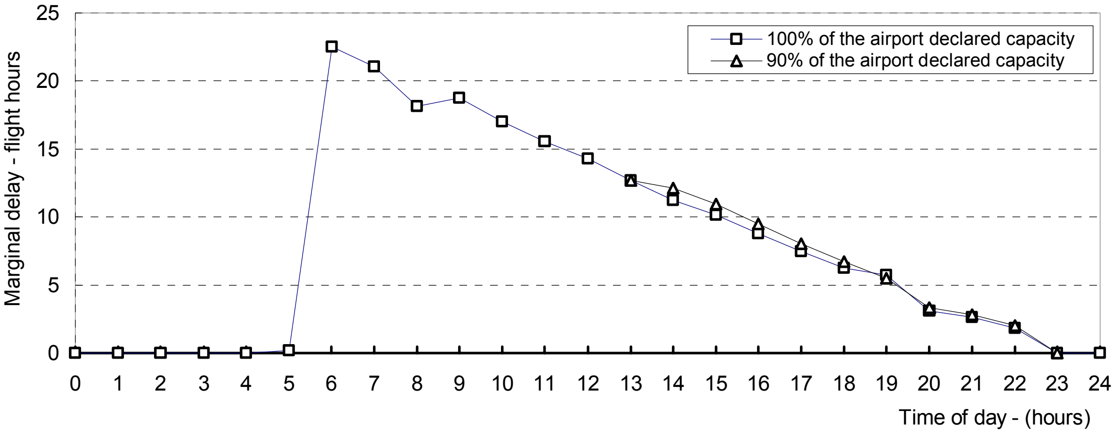
The results from the experiments with the model are shown in Figures 6, 7, and 8. Figure 6 (a, b, c) show the congestion and delays of flights caused by an additional flight.



a) Queue of flights



b) Delay of the last flight in the queue



c) Marginal delay imposed by an additional flight

Figure 6 The system congestion and delays in given example

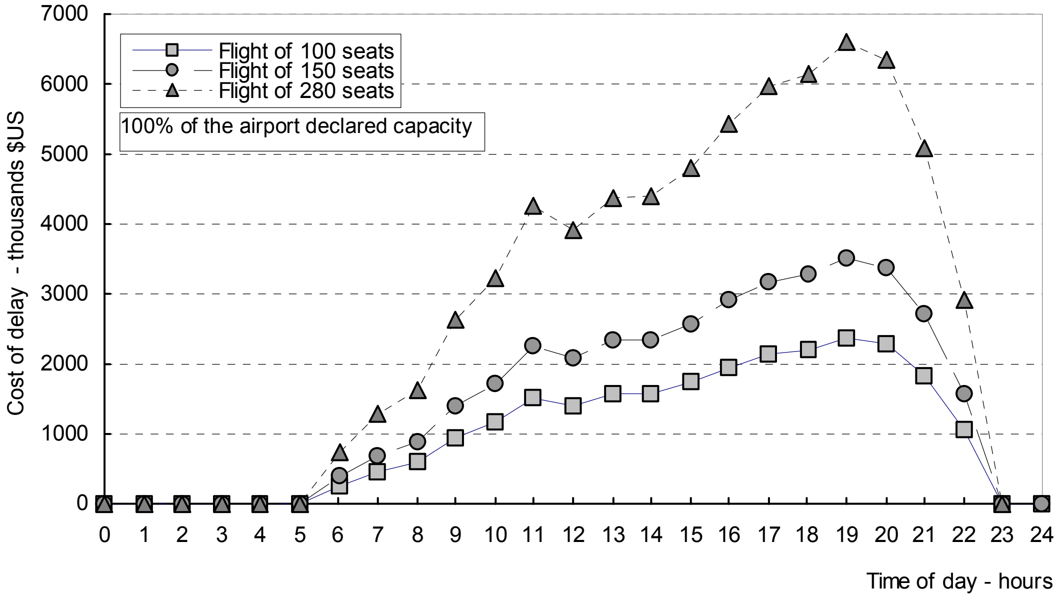
As can be seen in Figure 6a, during an average day, the queue of flights has started to form early in the morning just after opening the airport (06:00 hours), gradually increased afterwards, and reached the maximum between 19:00 and 20:00 hours. Then, during the next three hours (from 20:00 to 23:00 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 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 6b 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.

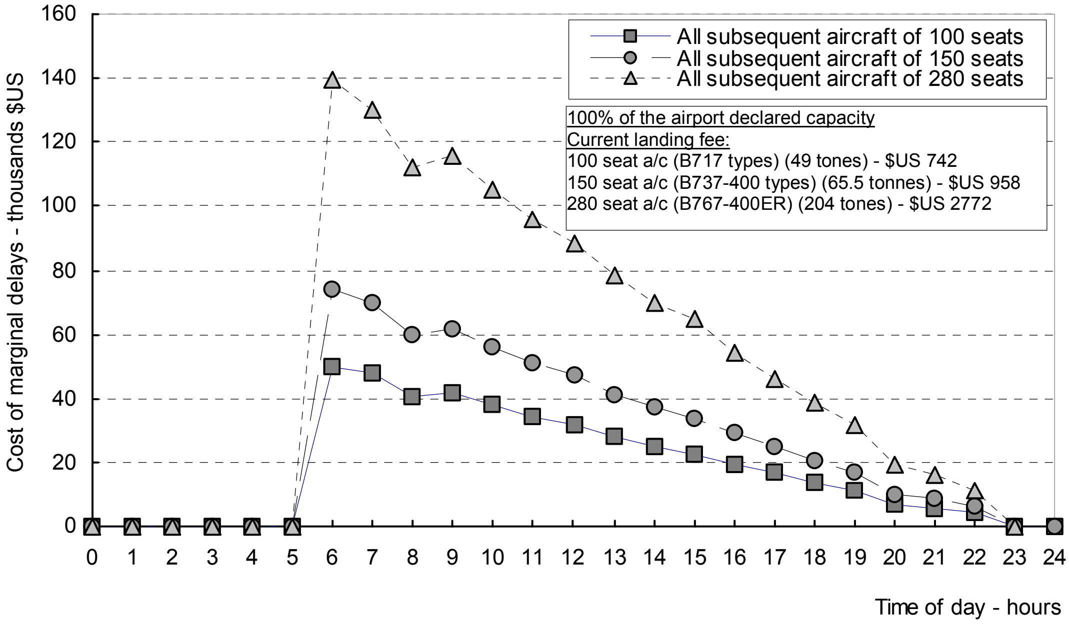
Figure 6c illustrates changes of the marginal delay caused by changing of the scheduling time of an additional flight.. As can be seen, the flight scheduled early in the morning has imposed longer marginal delay then otherwise. In the given example, one such flight scheduled at 06:00 hours has imposed about 22 additional flight-hours of delay on the succeeding flights scheduled by the end of the congestion period. Scheduling of the new flight latter during the day has affected the smaller number of succeeding flights and 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 these delays, as well as the flight private delay. As can be seen in Figure 6b and 6c, marginal delay imposed on others has been much greater than the flight private delay.

Figure 7 (a and b) shows the costs of an additional flight in the given example. Figure 7a 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 7b 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 if the additional flight has been scheduled early in the morning and gradually decreased if this flight has been scheduled latter 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 large disproportion. By summing up the costs of delays in Figure 7a and 7b, the costs of the total system delays caused by an additional flight have been obtained. Under such conditions, profitability of the additional flight has been estimated. Figure 8 shows conditions of such profitability in the given example. The additional flight of duration of 2 hours has been carried out by an aircraft of 150 seats with the operational cost of



a) Cost of delay of an additional flight



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

Figure 7 The system cost imposed by an additional flight in given example

$US3300, the average load factor of 60%, the average airfare of $US152 and consequently the revenue of $US136800. 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.

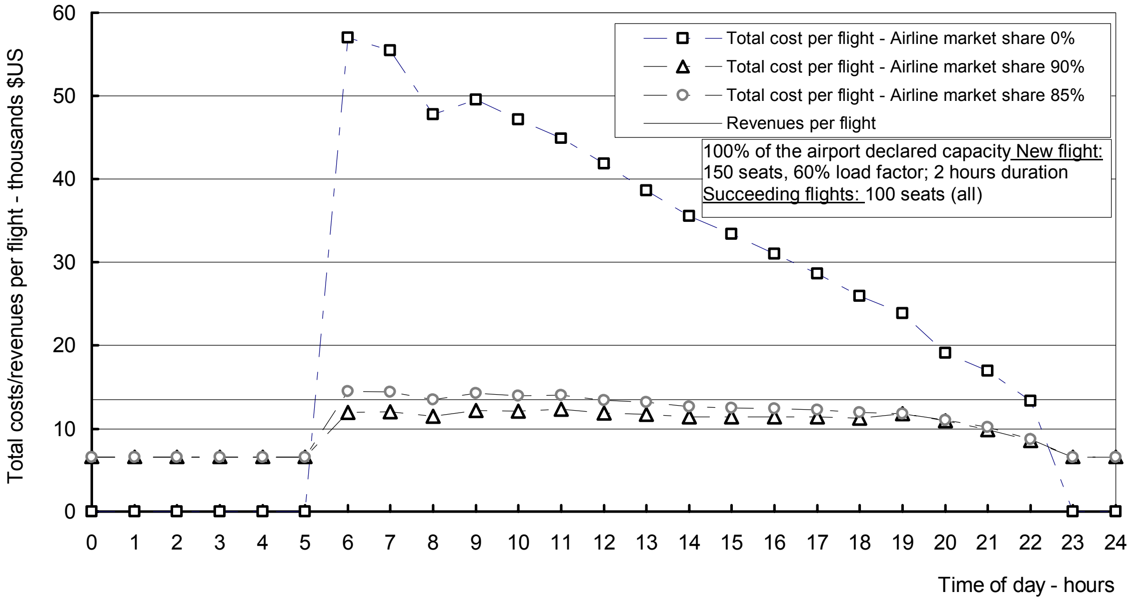


Figure 8 Conditions of profitability of an additional flight in given example

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 dealt with modelling of the congestion charging at airports. At present, congestion charging has not been practised at the airports worldwide despite many of them have already charged differently the services during the peak and off-peak periods. The modelling has consisted of three components: the queuing model based on the diffusion approximation used for estimation of the relevant queues and delays of flights; the model to estimate the marginal delays and their cost imposed on the succeeding flights by an additional flight during congestion; and the model for estimation of the profitability of an additional flight after being imposed the congestion charge on. The modelling procedure has been demonstrated on the example of New York (NY) LaGuardia airport.

The results have shown that the queues and delays of flights have persisted for the whole day. Decreasing of the airport declared capacity has increased these queues and delays, from the time of disruption on. The additional time has been needed to clear increased queues. The system cost of delays has raised in proportion to the delays and the aircraft size (i.e., seat capacity).

The additional flight scheduled at the beginning of the congestion period has imposed the greatest marginal delays, and vice versa. The marginal costs have increased in proportion to the increasing of these delays on the one hand and the size of the succeeding aircraft on the other, and vice versa.

The congestion charge has been lower for an additional flight scheduled by an airline having a greater market share since this flight has affected the smaller number of flights scheduled by other airlines, and vice versa. This has confirmed the fact that the congestion charging might disfavour competition at the airport.

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