The Economics of Airport Congestion Pricing

Paper for the The 7th ATRS World Conference
First Draft: do not quote without contacting the authors

Eric Pels Erik T. Verhoef
Free University Amsterdam, Department of Spatial Economics
De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands
Email: apels@feweb.vu.nl everhoef@feweb.vu.nl
telephone: +31-20-4446049 +31-20-4446094
fax: +31-20-4446004

Keywords: congestion, market power, networks, airports, airlines

1 INTRODUCTION

Many airports are facing capacity problems. In the U.S., 25 airports are classified as "severely congested" by the Federal Aviation Administration (Daniel, 2001), while also in Europe many airports face congestion problems (e.g. London Heathrow, Frankfurt and Amsterdam Schiphol).

In the U.S., the (runway) capacity of (larger) airports is usually allocated based on a first-come first-served principle. When capacity is limited, arriving aircraft cause delays (and thus costs) for other arriving aircraft. Only four US airports (Washington Ronald Reagan, New York LaGuardia, New York Kennedy and Chicago O'Hare) are slot-constrained; slot trading between airlines is allowed at these airports (see e.g Starkie, 1992). European airports are usually slot-constrained; slots are allocated by a slot coordinator. The slot-allocation mechanism at most airports is economically inefficient. The users of capacity (airlines) may pay less than the marginal social cost (congestion costs are not paid, entry is deterred), and are not necessarily the (potential) users that attach the highest economic value to the capacity.

Airport congestion pricing also to allocate scarce capacity to those parties that attach the highest economic value to it. Most studies of (second-best) congestion pricing in transport networks concern road traffic and consider link-based tolls. For other modes, however, it may often be nodes, rather than the links between them, that form the bottlenecks in a network. A question that naturally arises is whether insights from studies on link-based pricing are directly transferable to node-based pricing, especially under second-best circumstances where multiple market distortions exist simultaneously. It may be expected that the nature of other market distortions, additional to congestion externalities, will often be different at nodes than along links. Given the substantial and growing congestion at major airports and other transport hubs and nodes throughout the world, it seems highly relevant to investigate the implications for airport congestion pricing.

The economic nature of airports and their primary user(s) may indeed imply important deviations from the economic conditions governing a congested road network. In particular, individual road users would typically not have any market power, and can thus be assumed to take travel times and tolls (if any) as given (in practice, this would normally also hold for transport firms that may have multiple trucks using the same congested network simultaneously). Airports, in contrast, and especially the more congested hubs, will typically have spatial monopolistic power, while the primary user(s), airports, will often compete under oligopolistic conditions. Moreover, when positive network externalities (or economies of density) induce these airlines to use hub-and-spoke type networks, with different airlines using different hubs, these oligopolies may be asymmetric. A substantial share of congestion costs may then in fact not be external effects, but internal instead, in the sense that the travel delays imposed by one service upon other services would often concern services of that same operator, who can be assumed to take these firm internal congestion effects already into account when designing a profit-maximizing price and frequency schedule for the hub (Brueckner, 2002).

A further implication of oligopolistic competition would be that another distortion, besides congestion, is likely to be present, namely that of strategic interaction between competitors with the result of non-competitive pricing. Absent congestion, consumer prices may then exceed marginal costs, implying that an economic argument for subsidization rather than taxation would exist. As pointed out by Buchanan (1969) and Baumol and Oates (1988) in the context of a polluting monopolistic firm, the implication for Pigouvian externality pricing is that the second-best optimal tax would be below the marginal external costs and may even become negative. This would provide a second argument, in addition to the point raised by Brueckner (2002), of why optimal congestion charges at a hub would be below marginal external congestion costs if straightforwardly defined as the value of a single service's marginal delay costs for all other services.

This paper aims to investigate such issues in a network environment, by developing a model that is cast in terms of aviation and considers second-best congestion pricing for incoming and outgoing flights at airports. The model extends an earlier model of second-best pricing in congested road networks (Verhoef, 2002). The second-best circumstances under which congestion tolls have to be set are those just mentioned. We consider a simple network with multiple nodes, where both airlines and passengers suffer from congestion at airports. Three types of interacting players are present in our model: a regulatory authority, airlines, and passengers; each having their own objective. Congestion tolls can be determined by a single regulator for all airports in the network, but also by "local" regulators of specific airports. "Competition" between local regulators then becomes an issue. The insights developed may of course often carry over directly to congestion pricing at nodes for different modes than aviation, and possibly even different types of networks, provided market conditions are similar to those considered here.

Airport congestion pricing has already received some attention in the literature. Carlin and Park (1970) estimated the external cost of a peak-period landing at LaGuardia was $2000 (in 1969 $); about twenty times the actual landing fee, although this number should not be interpreted as an equilibrium congestion toll. Oum and Zhang (1990) examine the relation between congestion tolls and capacity costs, and find that when capacity investment is lumpy, the cost recovery theorem (which states that congestion toll revenues just cover amortized capacity (expansion) costs under constant returns to scale) no longer holds. Daniel (1995, 2001) combines stochastic queuing theory with a Vickrey-type bottleneck model, and simulation results show that congestion pricing causes a redistribution of flights over the day, where smaller aircraft may divert to other airports because they value their use less than the social cost of using the congested airport. Brueckner (2002) analyzes airport congestion pricing when airlines are nonatomistic, and concludes that there may be only a limited or even no role for congestion pricing when the number of airlines using the node decreases, as the share of internalized congestion costs increases. Brueckner (2003) analyzes airport congestion pricing in a network setting, and finds that the airline specific toll equals (one minus an airline's flight share) multiplied by the congestion damage caused by the airline.

The structure of the paper is as follows. First, the notation and assumptions will be presented in Section 2. Section 3 contains the (profit) maximization model for the network operators (airlines). Section 4 contains the regulator's optimization problem. Section 5 presents a simple numerical solution, and Section 6 concludes.

2 NOTATION AND ASSUMPTIONS

In the model, we distinguish three different parties. *Passengers* wish to travel between an origin and destination (a formulation with freight transport with atomistic demanders would be comparable to the one given here). In order to do so, services of an *airline* are necessary. Airlines, in turn, need the services of two (origin and destination) or more (in case of indirect services) airports. Prices for the use of the airport may be set by a profit maximizing *airport operator* or a welfare maximizing *regulatory authority*. Because we are concerned with (second-best) optimal airport prices, we will be considering a regulatory authority alone. An extension of the model to four types of players (regulators, airport operators, airlines and passengers) is considered as an interesting option for future work.

For the general specification of the model, a number of assumptions are made that will now be presented.

Assumption 1. A given passenger's trip in an origin- destination j pair will involve one airline only. The inverse demand function in each market is linear in form:

$$D_j\left(\sum_{i=1}^{I} q_{i,j}\right) = \alpha_j - \beta_j \sum_{i=1}^{I} q_{i,j} \tag{1}$$

where α_j and $\beta_j > 0$; α_j represents the maximum gross valuation by consumers in market j; $q_{i,j}$ is the number of passengers transported by airline i in market j, and β_j is the demand sensitivity parameter. A linear form is convenient in the numerical version of the model; for the analytical exposition it saves somewhat on the notation as the slope β_j is constant.

Assumption 2. Frequency on a link is

$$f_{i,k} = \frac{1}{\lambda_i} \sum_{j=1}^{J} \delta_{i,j,k} q_{i,j} \qquad ..(2)$$

where $\delta_{i,j,k}$ is a dummy equal to 1 if link k is used in market j by operator i and λ_i is the product of the load factor and the seat capacity. Congestion occurs at nodes only (*i.e.*, not on links; "capacity in the air" or the capacity of the air traffic control system is abundant). The average congestion costs per passenger or per flight (measured in additional travel time) at node h are assumed to increase linearly with the total frequency at the node:

$$\phi_h = \eta_h \sum_{k=1}^{K} \sum_{i=1}^{I} \delta_{k,h} f_{i,k} = \eta_h \sum_{k=1}^{K} \sum_{i=1}^{I} \delta_{k,h} \frac{1}{\lambda_i} \sum_{j=1}^{J} \delta_{i,j,k} q_{i,j} \tag{3}$$

where η_h is the constant slope of the congestion function and $\delta_{k,h}$ indicates the nodes used on links h. Note that arriving and departing movements need not contribute equally to, and suffer equally from congestion. However, as we only consider return markets, we do not have to make this distinction. The congestion term (in time units) to be included in the passengers' generalized cost function for alternative i in market j then is

$$\phi_{i,j} = \sum_{k=1}^{K} \sum_{h=1}^{H} \delta_{k,h} \delta_{i,j,k} \phi_h \tag{4}$$

where $\delta_{i,j,k}$ denotes the links used in market j and ϕ_h the congestion (measured in time) suffered at these nodes. Multiplying this term by the passengers' value of time yields the monetized congestion delay cost to passengers. Likewise, the term to be included in the airline cost function (over all flights, using link k, to passengers) is:

$$\phi_{i,k} = \sum_{j=1}^{J} \sum_{h=1}^{H} \delta_{k,h} \delta_{i,j,k} \phi_h \tag{5}$$

Assumption 3. The different alternatives i in market j are characterized by a generalized user cost function $g_{i,j}(p_{i,j}, vot_p \times \phi_{i,j})$ where $vot_p \times \phi_{i,j}$ represents the monetized average congestion costs per passenger (vot_p is the passenger's value of time) and $p_{i,j}$ is the fare. The generalized user cost function is linearly additive in form:

$$g_{i,j} = p_{i,j} + vot_p \times \phi_{i,j} \tag{6}$$

Assumption 4. The operator's cost per passenger $c^q_{i,k}$ and per transport movement $c^f_{i,k}$ are constant on each link. t_h is the congestion toll at node h. Total operating costs for operator i are then:

$$\sum_{k=1}^{K} \left(f_{i,k} \left(c^f_{i,k} + \sum_{h=1}^{H} \delta_{k,h} t_h + vot_l \times \phi_{i,k} \right) + c^q_{i,k} \sum_{j=1}^{J} \delta_{i,j,k} q_{i,j} - F_{i,k} \right) \tag{7}$$

which may be rewritten as:

$$\sum_{k=1}^{K}\left(\left[\sum_{m=1}^{J}\delta_{i,m,k}q_{i,m}\right]\times\left[\frac{1}{\lambda_i}\left(c_{i,k}^{f}+\sum_{h=1}^{H}\delta_{i,k,h}t_h+vot_l\times\phi_{i,k}\right)+c_{i,k}^{q}\right]-F_{i,k}\right) \tag{7'}$$

where $vot_l \times \phi_{i,k}$ represents the monetized average congestion costs per flight (vot_l is the airline's value of time). $F_{i,k}$ is airline i's fixed cost per link.

Assumption 5. Competing airlines on a specific market act as Cournot opligopolists (*i.e.* they choose an optimal output (and frequency) taking the others' outputs as given). Airlines do not believe that by their actions, they can affect the regulator's tolls (*i.e.* regulators and airlines are playing a Stackelberg type game, the regulators being the leader). Passengers are pure price takers.

Although these assumptions may seem restrictive, many of these assumptions are quite common in the aviation economics literature. The functional form of the cost function used in this paper is similar to the one used by Brueckner and Spiller (1991)[1]. Combined with a linear demand curve, the "Brueckner-Spiller" model has been used regularly in the literature to analyze aviation networks. Despite the conceptual simplicity (but, in case of large networks, computational complexity), recent trends in the aviation markets can easily be explained using this model; see e.g. Brueckner (2001) for an analysis of airline alliances, and Pels *et al.* (2001) for an analysis of optimal airline networks[2]. It is not the objective of this paper to calculate exact tolls for existing airports, for which these assumptions would clearly be too restrictive. This paper aims to develop theoretical insights into the consequences of airport congestion pricing, for which these assumptions suffice.

3 THE SYMMETRIC EQUILIBRIUM

With these assumptions, we can now turn to the derivation of optimal tolls. There are three types of players in the model (passengers, airlines and regulatory authorities), each with their own maximization problem. The model is solved in three steps. First, a passenger demand function for network operator i in market j is determined. Then, using this demand function, the airline problem is specified, and the associated profit maximizing optimality conditions

[1] Brueckner and Spiller (1991) do not include congestion in their cost function.
[2] See Brueckner (2001) for additional references.

are derived. Finally, the regulator's problem is solved, again using the passenger demand function, and also using the operator optimality conditions as restrictions.

To determine the equilibrium, we focus on a simple network with two airports and two airlines offering services in one market only (see Figure 1). For convenience, we assume that both airlines use aircraft of similar capacity and that marginal costs per passenger (flight) are the same for both airlines. Although this assumption is not necessary to determine the equilibrium, it greatly reduces the notation. These assumptions are relaxed in a numerical exercise.

Figure 1 *Network configuration*

In this network, congestion tolls are the same for both airports (due to symmetry). Moreover, The congestion toll cannot be distinguished from the subsidy necessary to encounter the market-power effect. Hence, only a toll t appears in the airline cost functions.

The passenger optimization problem

The maximum willingness to pay for the marginal passenger in market j for alternative i, including monetized time costs, is given by equation (1), while each passenger's generalized user cost for the use of operator i are given by $g_{i,j}(\cdot)$ as defined in equation (6). Intra-marginal passengers' net benefits are determined according to the familiar Marshallian surplus. According to Wardrop's equilibrium conditions, marginal benefits are equal to the average generalized costs in equilibrium (or marginal net benefits are zero) for all used alternatives (operators in this case), so that $D_j(..)=g_{i,j}(..)\ \forall\ i$ in equilibrium, while the average generalized costs of unused alternatives cannot be lower than $D_j(..)$ and will typically be higher. Because operators incur costs for a service also when $q_{i,j}=0$ (see (7)), unused alternatives in our model will not actually be offered. By assumption, demand and generalized cost functions are linear, so that the equilibrium condition for both airlines in the simple network implies:

$$
\begin{aligned}
p_1 &= \alpha - \beta(q_1+q_2) - 2\eta_h vot_p \frac{q_1+q_2}{\lambda} \\
p_2 &= \alpha - \beta(q_1+q_2) - 2\eta_h vot_p \frac{q_1+q_2}{\lambda}
\end{aligned}
\tag{8}
$$

where α is the constant in the inverse demand function and β is the slope of the inverse demand function. This operator specific inverse demand curve incorporates passengers' optimizing behavior, and is used in the next step to maximize operator profits. Note that the arguments of this inverse demand function include the quantities sold by competing airline.

The transport network operator maximization problem

As stated in assumption 5, we assume Cournot behavior in modeling airline competition. This is motivated by earlier (empirical) research.[3] In a Cournot oligopoly, excess profits can be made when the number of suppliers is finite. For the alternative of Bertrand-competition, equilibrium prices would equal marginal costs without collusion, when marginal costs are constant (as they are in this model). The current financial problems of many airlines does not mean that Cournot oligopoly modeling would not be appropriate for this sector. High fixed costs may contribute to financial problems, also under Cournot-competition.

Thus, the operators in this model maximize profits with respect to $q_{i,j}$, taking the competitors quantities as given (note that the assumption of a fixed passenger load implies that maximization with respect to frequencies independent of passenger numbers is neither possible nor necessary). In general, the maximization problem for operator i is:

$$\max_{q_i} \pi_i = \left[\alpha - \beta(q_1 + q_2) - 2vot_p \eta_h \frac{q_1 + q_2}{\lambda}\right] q_i - q_i \left[\frac{c^f + 2t + 2vot_l \eta_h \frac{q_1 + q_2}{\lambda}}{\lambda} + c^q\right] - F \quad (9)$$

The first-order necessary conditions for i=(1,2) are:

[3] For instance, in an empirical analysis of Chicago-based airline routes involving American Airlines and United Airlines, Oum et al. (1993) conclude that "the overall results indicate that the duopolists' conduct may be described as somewhere between Bertrand and Cournot behavior, but much closer to Cournot, in the majority of the sample observations". Brander and Zhang (1990), using similar data, find " strong evidence … against the highly competitive Bertrand hypothesis". Brander and Zhang (1990) find Cournot behavior plausible for the markets under consideration (Chicago-based routes where American Airlines and United Airlines together have a market share exceeding 75%). Based on these observations, we assume Cournot competition.

$$\alpha - \beta(q_1 + q_2) - 2vot_p \eta_h \frac{q_1 + q_2}{\lambda} - q_i \left(\beta + \frac{2vot_p \eta_h}{\lambda} \right) - \left[\frac{c^f + 2t + 2vot_l \eta_h \frac{q_1 + q_2}{\lambda}}{\lambda} + c^q \right] - q_i \frac{2vot_l \eta_h}{\lambda^2} = 0 \tag{10}$$

Each additional passenger transported by airline i causes a congestion cost $2\eta_h vot_l / \lambda^2$ for both airline i and airline $-i$. Likewise, a congestion cost of $2\eta_h vot_p / \lambda$ is imposed on the passengers transported by both airline i and airline $-i$. From the first-order condition for profit maximization, it is apparent that airline i only internalizes the congestion incurred by itself or its passengers (the last LHS-term and the fourth LHS-term respectively). Because the airlines have the same outputs in the symmetric equilibrium, it follows that the airlines internalize half of the congestion they are responsible for (the same result is obtained by Brueckner, 2003). Solving the first-order conditions yields the following optimal outputs:

$$q_1 = q_2 = \frac{1}{3} \frac{\lambda[\alpha\lambda - 2t - c^l - \lambda c^q]}{\beta\lambda^2 + 2\eta(\lambda vot_p + vot_l)} \tag{11}$$

which are positive when

$$\alpha > \frac{2t + c^l + \lambda c^q}{\lambda_l} \tag{12}$$

The latter condition simply states that outputs are positive when the passengers' gross valuation of an airline service exceeds the average cost of the service.

From the first-order condition and the generalized cost function, we can derive the fare:

$$p_i = \left[\frac{1}{\lambda} \left(c_i^f + 2t + 2vot_l \eta_h \frac{q_1 + q_2}{\lambda} \right) + c^q \right] + q_i \left(\beta + \frac{2vot_p \eta_h}{\lambda} + \frac{2vot_l \eta_h}{\lambda^2} \right), \quad \forall i = 1,2 \tag{13}$$

The first RHS-term (in square brackets) is the airline's operating cost per passenger. The second RHS-term consists of a mark-up over the marginal costs of i) $q_i(2\eta_h/\lambda)(vot_p + vot_l/\lambda)$ reflecting internalization of congestion costs and ii) $q_i\beta$ reflecting "residual" market power. Because airlines have market power, they are able to internalize congestion. But there is a "residual" market power effect which causes fare to exceed the welfare maximizing fare.

By construction, p_1=p_2, so that the fare is (after substituting the optimal values for the qs):

$$p = \frac{\beta\lambda^2\left(\alpha + c_1^q + c_2^q\right) + \left[\beta\left(c_1^l + c_2^l + 4t\right)\right]\lambda + 2\eta_h\left\{\left[\alpha + \left(c_1^q + c_2^q\right)\right]vot_p\lambda + 3\alpha vot_k + vot_p\left(4t + c_1^l + c_2^l\right)\right\}}{\beta\lambda^2 + 2\lambda vot_p + 2vot_l} \tag{14}$$

It follows from (14) that the equilibrium value for $q_{i,j}$ is a function of the toll t_h if $\delta_{k,h}$=1. The optimal toll is determined by the regulator.

The regulator's maximization problem

From the analysis in the preceding subsection, it is clear that there is large congestion effect that is not internalized by the carriers. In this section, we formulate strategies for a regulator to "fix" problem.

In terms of objectives, we consider welfare-maximizing regulation. Since there is a market-power effect, which, considered in isolation, requires a subsidy, the resulting optimal toll may be negative. Because both airlines have the same operating characteristics, and demand is shared evenly between the carriers, a regulator will set only one toll; this toll is paid by both airlines for both the usage of both airports. In the asymmetric equilibrium, differentiated tolls $t_{h,i}$ are necessary. Moreover, in networks with more than two nodes, it has to be acknowledged that congestion occurs at the airport level, while market power occurs at the market-level.

The global regulator maximizes surplus for the entire network: the regulator considers consumer surplus in *all* markets and profits of *all* operators. It sets a common toll t for all nodes h in the system. The authority thus maximizes the following objective function:

$$\max_{t_h} \varpi_G =$$

$$\sum_{j=1}^{J} \int_{0}^{\sum_{i=1}^{I} q_{i,j}} D_j(x)dx - \sum_{i=1}^{I}\sum_{j=1}^{J} q_{i,j} vot_p \phi_{i,j} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} \delta_{i,j,k} q_{i,j} \left[\frac{1}{\lambda_i}\left(c_{i,k}^{f} + vot_l \times \phi_{i,k}\right) + c_{i,k}^{q} \right] \tag{15}$$

The first right hand side (rhs) term represents total benefits (as integral of the Marshallian inverse demand function). The second rhs term represents total generalized costs (excluding the airline fares, which cancel out against the airline revenues). The third rhs term represents airline operating costs (excluding the expenditures on tolls, which cancel out against toll revenues). The three terms together thus give social surplus. The regulator sets the toll t_h, given the airline (profit maximizing) optimality conditions. A change in t_h affects the optimal output, and thus total welfare. Substituting the airlines' optimal outputs (which are functions of t_h) in the welfare function and maximizing over t_h yields the equilibrium in quantities and tolls. For the network in Figure 1, the maximization problem is:

$$\max_{q_i} \varpi_G = \int_{0}^{2q} (\alpha - \beta x)dx - 2(q_1 + q_2)\frac{(q_1 + q_2)vot_p \eta_h}{\lambda} - 2q\left[\frac{1}{\lambda_i}\left(c^f + vot_l \frac{2q}{\lambda}\right) + c^q\right]$$

(16)

Comparing the first-order conditions for welfare maximization and profit maximization yields:

$$\frac{\partial \varpi_G}{\partial q_i} - \frac{\partial \pi_G}{\partial q_i} = -q_{-i}\frac{2\eta_h}{\lambda}\left(vot_p + \frac{vot_k}{\lambda}\right) + q_i\beta + \frac{2t}{\lambda} \tag{17}$$

where the first RHS-term is the congestion that is not internalized by carrier i and the second RHS-term is the market power effect. Ideally, the toll would be set to fix both the congestion and market power problems. Following Brueckner (2003), the regulator may set a toll that charges the airline for the congestion that is not internalized:

$$t^c = q\left(vot_p + \frac{vot_k}{\lambda}\right) = \frac{\eta_h}{3}\frac{(\lambda vot_p + vot_k)[\alpha\lambda - c^l - \lambda c^q]}{\beta\lambda^2 + 2\eta(\lambda vot_p + vot_l)} \tag{18}$$

which is necessarily positive when q>0 (i.e. when (12) holds). Likewise, the subsidy necessary to encounter the market power effect is:

$$s = -\frac{\beta\lambda^2}{3}\frac{\left(\alpha\lambda - c^q\lambda - c^f\right)}{\beta\lambda^2 + 2\eta\left(\lambda vot_p + vot_l\right)} \tag{19}$$

The subsidy would be given on a market level, while the toll would be levied at the airport level (and both are carrier-specific). In the symmetric equilibrium for a network with only market, one can not distinguish between airport and market specific tolls, because both depend on the passenger flow in a single market.

A welfare maximizing regulator will thus set a toll

$$t = t^c + s = \frac{1}{3}\frac{\left(2\eta_h\left(\lambda vot_p + vot_k\right) - \beta\lambda^2\right)\left[\alpha\lambda - c^l - \lambda c^q\right]}{\beta\lambda^2 + 2\eta\left(\lambda vot_p + vot_l\right)} \tag{20}$$

Condition (12) for positive qs implies that $\alpha > \left(c^l + \lambda c_2^q\right)/\lambda$, so that the second term in the numerator is positive. The toll is negative when $2\eta_h\left(\lambda vot_p + vot_l\right) - \beta\lambda^2 < 0$; i.e. when the "residual" market power effect $q_i\beta$ in the fare-equation (13) is larger than the congestion effect $q_i\left(2\eta_h/\lambda\right)\left(vot_p + vot_l/\lambda\right)$. Since subsidization may not be feasible in practice, so that the regulator may set a congestion toll only, as in (18). Note that this toll will not maximize welfare. In fact, to maximize welfare, output should be increased (because the market power effect dominates), while output is decreased by the toll (it can be shown that $\partial[\text{consumer benefits}]/\partial t$ evaluated at t as given in (18) is always negative). The toll in (18) does not take into account any losses in consumer benefits

Finally, using (11), we find that the toll equals (1-flight share)×damage, as in Brueckner (2003), when we would set airline specific tolls, although this rule has little meaning in the symmetric case. The asymmetric case, with airport specific congestion tolls and market specific subsidies, will be analyzed in the next section.

Variations on the regulator's maximization problem

The tolls in the previous subsection are "first-best" in the sense that total welfare is maximized without any restrictions. In practice, it may be, however, that the airlines play a Stackelberg-type of game, in which the authorities first set a welfare-maximizing congestion toll, to which the airlines then respond. In effect, welfare is them maximized with respect to the toll, after the optimal qs are substituted in the welfare function:

$$\max_{t_h} \varpi_G = \int_0^{2q^*} (\alpha - \beta x) dx - 2q^* vot_p \frac{2q^*}{\lambda} - 2q^* \left[\frac{1}{\lambda_i} \left(c^f + vot_l \frac{2q^*}{\lambda} \right) + c^q \right] \tag{21}$$

The first-order necessary condition for welfare maximization is

$$(\alpha - 2\beta q^*) 2 \frac{\partial q^*}{\partial t} - 8 vot_p \frac{q^*}{\lambda} \frac{\partial q^*}{\partial t} - 2 \frac{\partial q^*}{\partial t} \left[\frac{1}{\lambda} \left(c^f + vot_l \frac{2q^*}{\lambda} \right) + c^q \right] - \frac{4q^*}{\lambda^2} vot_l \frac{\partial q^*}{\partial t} = 0 \tag{22}$$

The interpretation of the first-order condition is as follows. A change in t causes a change in q, and thus also the consumer benefits; this is indicated by the first LHS-term. Furthermore, because the total number of passengers changes, total congestion costs change. This is indicated by the second LHS-term. Airline (operating and congestion) costs also change, as indicated by the third and fourth RHS-term. Solving the first-order condition yields the following toll rule:

$$t = \frac{1}{4} \frac{(\alpha\lambda - c^q \lambda - c^l)(2\eta_h [\lambda vot_p + vot_l] - \beta\lambda^2)}{\beta\lambda^2 + 4\eta_h (vot_p \lambda + vot_l)} \tag{23}$$

Comparing (23) and (20), we see that the second-best (Stackelberg) toll exceeds the welfare maximizing toll. This stands to reason. When the airlines and the regulator play a Stackelberg-game (rather than the game in which the regulator sets a first-best welfare maximizing toll), airline profits will most likely be higher because airlines maximize their profits. A lower output means lesser congestion damage, so that the congestion part of the toll is lower than the congestion toll in (18). The market power subsidy will be necessarily higher (in absolute value) compared to the subsidy in (19), but because the congestion effect dominates, the overall toll is lower (in absolute value).

4 NUMERICAL ANALYSIS

In this section, numerical solutions for the network in Figure 1 are presented. These solutions serve two purposes. Firstly, they allow us to check the welfare effects of a pure congestion toll in a market where (symmetric) airlines have market power. Secondly, we can analyze the asymmetric equilibrium, for which the analytical solutions are more difficult to interpret.

The necessary demand characteristics are given in Table 2; airline characteristics in Table 3, and airport characteristics in Table 4. It is not the purpose of this paper to accurately describe a real-life aviation network. The parameters therefore may also not correspond to real life values. In the simulation, we will calculate the price elasticity of demand and compare this estimates from the literature to validate our results.

α	30000
β	4

Table 1. Demand characteristics

λ	200	c^f	100000	c^q	100

Table 2. Transport network operator characteristics

vot_l	50	η_A	0.5
vot_p	5		

Table 3. Node characteristics

Table 4 contains the no-toll equilibrium. The calculated price elasticity in equilibrium of -1.17 roughly corresponds to the value of -1.146 reported by Brons et al. (2002). The latter number is the overall mean of 204 estimates encountered in the literature. The model thus yields an elasticity in equilibrium that corresponds to real life values; we operate on a relevant segment of the demand curve.

		generalized costs			welfare effects ($\times 10^7$)		
	q	fare	congestion	ε_{price}	local welfare	consumer benefits	profits
airline 1	1862	10447	931	1.17	3.45894	3.85275	1.72499
airline 2	1862	10447	931	1.17	3.45894	3.85275	1.72499

Table 4. Equilibrium outputs and welfare; no toll, elasticity in absolute value

Table 5 contains the equilibrium for the (first-best) welfare maximizing toll (given in equation (20)). The toll is negative, and quite large in absolute value (compared to, for instance, the marginal cost per flight). This indicates that the market power effect in the no-toll equilibrium exceeds the congestion effect. Because the airlines receive substantial subsidies, the optimal outputs and profits are larger than in the no-toll equilibrium. Because the optimal outputs are higher, congestion costs are also higher. In the no-toll equilibrium, the airlines set their optimal outputs too low, and as a result, the congestion costs are too low in the optimum. The welfare maximizing toll fixes this problem.

		generalized costs				welfare effects ($\times 10^7$)	
	q	fare	congestion	ε_{price}	local welfare	consumer benefits	profits
airline 1	2390	4904	1195	0.46	3.77069	8.62801	2.90621
airline 2	2390	4904	1195	0.46	3.77069	8.62801	2.90621

Table 5. Equilibrium outputs and welfare; first-best welfare maximizing toll = -833349; *elasticity in absolute value*

The equilibrium in Table 5 may only be of academic interest, because subsidizing airlines may be politically rather tricky. Brueckner (2003) suggests that the toll in such a case should be set at the level of congestion that is not internalized by the airlines (equation (18)). This equilibrium is given in Table 6.

		generalized costs				welfare effects ($\times 10^7$)	
	q	fare	congestion	ε_{price}	local welfare	consumer benefits	profits
airline 1	1800	11097	900	1.28	3.40219	7.56073	1.60563
airline 2	1800	11097	900	1.28	3.40219	7.56073	1.60563

Table 4. Equilibrium outputs and welfare; Brueckner-toll = 97767; *elasticity in absolute value*

The toll is positive (as expected), and this is also reflected in consumer prices (the airlines pass the toll on to the passengers). Because the fares increase, consumer benefits decrease. From Table 4 and 5 we already concluded that in the no-toll equilibrium, the airlines set their optimal outputs, and thus also the congestion costs, too low. The 'Brueckner-toll" causes the outputs to be even lower. Combined with the decrease in consumer benefits, this leads to a decrease in total welfare. The straightforward conclusion then is that in this market the regulator should set welfare maximizing tolls. If this is not possible, the regulator should do nothing. Pure congestion tolls do more harm than good.

When we take the first-best optimum as a reference case, it could be more for the airlines to act as followers in a Stackelberg-like game with the airports authorities. The airports then set a toll to which the airlines respond; in practice, this means that the optimal outputs from the airline point of view are substituted in the regulator's objective function. The airlines thus obtain the maximum possible profits, conditional on the toll, while this is not the case in the first-best optimum. Because the airlines receive a subsidy for each passenger they move, they maximize the output up to the point where the "production" costs, including congestion costs, of the marginal passenger exceed the revenues (including subsidy). This is reflected in Table 6. The optimal output exceeds the optimal output in the first-best optimum. In theory, the airlines thus have an incentive to act as followers.

		generalized costs			welfare effects ($\times 10^7$)		
	q	fare	congestion	ε_{price}	local welfare	consumer benefits	profits
airline 1	2661	2063	1330	0.21	3.81113	8.88483	.3.62531
airline 2	2661	2063	1330	0.21	3.81113	8.88483	.3.62531

Table 6. Equilibrium outputs and welfare; second-best welfare maximizing toll = -1260480; *elasticity in absolute value*

CONCLUSION

Conventional economic wisdom suggests that congestion pricing would be an appropriate response to cope with the growing congestion levels currently experienced at many airports. Several characteristics of aviation markets, however, may make naïve congestion prices equal to the value of marginal travel delays a non-optimal response. This paper has developed a model of airport pricing that captures a number of these features. The model in particular reflects that airlines typically have market power and are engaged in oligopolistic competition at different sub-markets; that part of external travel delays that aircraft impose are internal to an operator and hence should not be accounted for in congestion tolls. We presented an analytical treatment for a simple bi-nodal symmetric network, which through the use of 'hyper-networks' would be readily applicable to dynamic problems (in discrete time) such as peak – off-peak differences, and some numerical exercises for the same symmetric network, which was only designed to illustrate the possible comparative static impacts of tolling, in addition to marginal equilibrium conditions as could be derived for the general model specification.

Some main conclusions are that second-best optimal tolls are typically lower than what would be suggested by congestion costs alone and may even be negative, and that the toll as derived by Brueckner (2002) may not lead to an increase in total welfare.

While Brueckner (2002) has made clear that congestion tolls on airports may be smaller than expected when congestion costs among aircraft are internal for a firm, our analysis adds to this that a further downward adjustment may be in order due to market power. The presence of market power (which causes prices to exceed marginal costs) may cause the pure congestion toll to be suboptimal, because the resulting decrease in demand is too high (the pure congestion toll does not take into account the decrease in consumer surplus).

The various downward adjustments in welfare maximizing tolls may well cause the optimal values of these to be negative. Insofar as subsidization is considered unacceptable for whichever reason, our results warn that the most efficient among the non-negative tolls may actually be a zero toll; the pure congestion toll may actually decrease welfare compared to the base case.

The model in this paper contains a few simplifying assumptions that may be relaxed in future work. Load factors and aircraft capacity are fixed in this model for simplicity. In a more advanced version of this model, load factors and aircraft capacity can be endogenized. This makes the derivation of the optimality conditions far more complicated, but it should be feasible in a numerical experiment. One can also add a fourth layer to the model, describing the airport's optimization problem. For example, the airport can maximize profits under a cost recovery constraint. The model then deals with interactions between four types of agents. No distinction is made between peak and off-peak traffic in this paper. This distinction is quite common in the literature (see e.g. Brueckner (2002), Daniel (1995)) and could, as discussed, make a straightforward but important extension of the model in this paper. Finally, the results of the numerical exercise in this paper need to be checked against an asymmetric equilibrium.

REFERENCES

Adler, N. and J. Berechman (2001), Evaluating optimal multi-hub networks in a deregulated aviation market with an application to Western Europe, *Transportation Research*, **35A**, 373-390.

Baumol, W.J. and W.E. Oates (1988), *The theory of environmental policy*, second edition, Cambridge University Press

Brander, J.A. and A. Zhang (1990), Market conduct in the airline industry: an empirical investigation, *Rand Journal of Economics*, **21**(4), 567-583

Brueckner, J.K. (2001), The economics of international codesharing: an analysis of airline alliances, *International Journal of Industrial Organization*, **19**, 1475-1498

Brueckner, J.K. (2001), Airport congestion pricing when carriers have market power, *American Economic Review*, forthcoming.

Brueckner, and P.T. Spiller (1991), Economics of traffic density in a deregulated airline industry, *International Journal of Industrial Organization*, **37**, 323-342

Buchanan, J.M. (1969), External diseconomies, external taxes, and market structure, *American Economic Review*, **59**, 174-177

Carlin, A. and R. Park (1970), Marginal cost pricing of airport runway capacity, *American Economic Review*, **60**, 310-319

Daniel, J.I. (2001), Distributional consequences of airport congestion pricing, *Journal of Urban Economics*, **50**, 230-258.

Daniel, J.I. (1995), Congestion pricing and capacity of large hub airports: a bottleneck model with stochastic queues, *Econometrica*, **63**, 103-130

Hendricks, K., M. Piccione and G. Tan (1999), Equilibria in networks, *Econometrica*, **67**, 1407-1434

Mohring, H. (1972), Optimization and scale economies in urban bus transportation, *American Economic Review*, **62**, 591-604

Oum, T.H., A. Zhang and Y. Zhang (1996), A note on optimal airport pricing in a hub-and-spoke system, *Transportation Research*, **30B**(1), 11-18

Oum, T.H., A. Zhang and Y. Zhang (1993), Inter-firm rivalry and firm-specific price elasticities in deregulated airline markets, *Journal of Transport Economics and Policy*, **27**, 171-192

Oum, T.H. and Y. Zhang (1990), Airport Pricing, Congestion tolls, lumpy investment and cost recovery, *Journal of Public Economics*, **43**, 353-374

Pels, E., P. Nijkamp and P. Rietveld (2000), A note on the optimality of airline networks, *Economics Letters*, **69**(3), 429-434

Verhoef, E.T., P. Nijkamp and P. Rietveld (1996), Second-best congestion pricing: the case of an untolled alternative, *Journal of Urban Economics*, **40**(3), 279-302

Verhoef, E.T. (2002), Second-best congestion pricing in general static transportation networks with elastic demands, *Regional Science and Urban Economics*, **32**, 281-310