Economics of Transportation (2014) 90–101

Contents lists available at ScienceDirect

Economics of Transportation

journal homepage: www.elsevier.com/locate/ecotra

Airport peak-load pricing revisited: The case of peak and uniform tolls

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ARTICLE INFO

Keywords:
Airports
Peak-load pricing
Schedule delays
Uniform tolls
Bottleneck

ABSTRACT

This paper develops a two-period model with peak/off-peak demands that incorporates three types of passengers: (1) passengers who are scheduled for peak departure and depart during the peak period, (2) passengers who are scheduled for peak departure but depart during the off-peak period because of congestion, and (3) passengers who are scheduled for off-peak departure. An increase in peak supply may turn own type-1 passengers into type-2 passengers, which is called self-imposed schedule delay. Our main result is that carriers with market power internalize self-imposed schedule delay costs. The investigation of a uniform-toll regime reveals that the welfare-optimal uniform toll corrects for external schedule delay only if schedule delay cost is sufficiently high.

1. Introduction

Twenty percent of airline flights in the United States were delayed between 2000 and 2007. The problem got worse in the first half of 2008, with 29% of the flights being delayed or canceled.[1] The causes of delays can vary across countries, but the high volume of traffic relative to airport capacity (mainly runway capacity) has been identified as a major cause. An "obvious" solution is to add more airport (runway) capacity. Economists have nevertheless advocated the use of the price mechanism, under which landing fees are based on a flight′s contribution to congestion, with early models by, for example, Levine (1969), Carlin and Park (1970) and Borins (1978). Although variations of congestion pricing were (partially) implemented at airports in Boston, New York and London (Schank, 2005), congestion pricing has not really been practiced. The existing landing fees in the US depend on aircraft weight and on passenger quantities, and the fee rates are based on the accountancy principle of cost recovery required usually for a public enterprise.[2] In view of the more recent airport delays, the US Department of Transport identified congestion reduction as its No. 2 top management challenge, only second to aviation safety (USDOT, 2008c), and has since 2008 allowed US airports to charge peak-period landing fees in addition to weight-based fees (USDOT, 2008a, 2008b).

The earlier congestion pricing models were developed along a line similar to dealing with road congestion. As such, flights (individual drivers) were treated as atomistic. Daniel (1995) was the first to study the role of a dominant carrier for airport congestion pricing. He derived numerical results (calibrated with data from Minneapolis–St. Paul airport in the US) based on a bottleneck model with stochastic queues,[3] which features a maximum of one dominant carrier, a set of atomistic airlines (the competitive fringe) and uniform preferences for operating times.[4] In this model, carriers use airport capacity during the preferred operating times in order to reduce schedule delays (the absolute difference between preferred and actual travel times); traffic volume may, however, become excessive relative to capacity, which means that passengers may be pushed away from preferred operating times by congestion. An important, and somewhat

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[1] Ball et al. (2010) studied the economic impact of air travel delays in the US. They found that the total cost of transport delays in 2007 was $31.2 billion, of which $8.3 billion were borne by airlines due to increased expenses for crew, fuel and maintenance, among others. $16.7 billion were borne by passengers due to, for example, delayed flights, flight cancellations and missed connections. The final $2.2 billion costs were based on an estimate of the welfare loss incurred by passengers who avoid air travel as the result of delays. Indirect effects were estimated to reduce gross domestic product by further $4 billion. Ball et al. did not consider that delays would also lead to emissions and other environmental problems. Similar delays have plagued European and Asian airlines and airports. In China (the world′s second largest air transport market behind the US) for example, more than 30% of its domestic flights were delayed in recent years.

[2] Zhang (2012) discusses airport improvement fees, which are typically charged on a per-passenger basis.

[3] In Daniel′s, 1995 model (as well as in Daniel′s subsequent studies), queues are stochastic in the sense that differences between scheduled and actual arrival and departure times are determined by exogenous random shocks. Notice that actual arrival and departure times refer to the moment where an aircraft joins the queue.

[4] Daniel (2001) extends the basic framework developed in his 1995 paper in order to capture elastic demands and heterogeneity in the preferences for operating times.

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http://dx.doi.org/10.1016/j.ecotra.2013.11.001

surprising, result of Daniel′s analysis is that the existence of a dominant carrier may have no effect on the level and structure of welfare optimal airport congestion prices at all. The intuition is that fringe carriers would take advantage of any attempt to reduce congestion during preferred operating times (since preferences for operating times are assumed to be the same for all carriers), which eliminates any incentives to do so. Thus, carriers should be treated as atomistic whether there is a dominant carrier or not.[5] Similar results are derived by Brueckner and van Dender (2008) and Silva et al. (2013) who use a static framework and a deterministic bottleneck model, respectively.[6]

A different approach was developed by Brueckner (2002). He considers a peak/off-peak (POP) model with one congested peak period, one uncongested off-peak period and an arbitrary number of identical carriers that compete in quantities a la Cournot.[7] In his model, all passengers who are scheduled for arrival/departure during peak hours are assumed to be served during peak hours in spite of congestion. Brueckner finds the intuitive result that congestion is reduced by carrier market power in equilibrium because carriers recognize that they impose congestion on themselves and therefore reduce supply. He further provides some empirical evidence, which supports his results on self-internalization.[8] Other examples for studies that rely on POP models of the Brueckner type are Basso and Zhang (2008) and Yuen and Zhang (2011) who, respectively, compare public versus private peak and off-peak pricing behavior of airports and analyze the role of variable time valuations for airport congestion pricing.

The contribution of the present paper is to extend the Brueckner POP approach in order to capture that passengers who cannot be accommodated during peak hours are diverted to the off-peak period. In this sense, the model developed in this paper integrates a crucial element of bottleneck models (changes in travel times because of limited capacity) into a POP framework with only two periods. Specifically, passengers scheduled for peak departure (or peak arrival) may depart (or arrive) during the peak period with some probability, which is decreasing in the aggregate quantity of scheduled peak departures (called peak supply).[9] In this setup, we can clearly distinguish between three types of passengers: (1) passengers who are scheduled for peak departure and depart during the peak period, (2) passengers who are scheduled for peak departure but depart during the off-peak period because of congestion, and (3) passengers who are scheduled for off-peak departure (and depart during the off-peak period). Note that an increase in peak supply may leave the aggregate quantity of type-1 passengers unchanged but increases the quantity of type-2 passengers. To our knowledge, this is the first paper that identifies and analyzes an environment with these three types of passengers, which can be used to analyze in a most transparent way the carriers′ incentives to internalize self-imposed schedule delays in the sense that an increase in peak supply may turn own type-1 passengers into type-2 passengers.

This paper concentrates on vertical differentiation in the sense that all passengers prefer a departure during the peak period relative to a departure during the off-peak period when ticket prices are the same and congestion is absent.[10] Airlines are however assumed to charge a premium for peak-period services, and this premium is determined by a (positive) *schedule parameter*, which determines the passengers′ schedule delay costs that arise from off-peak departures, and per-passenger congestion costs. Passengers are then indifferent between peak departure and off-peak departure in equilibrium. Taken together, this allows us to abstract away from passenger choices of departure times and concentrate on airline scheduling behavior. More specifically, after the airport determines tolls for the peak and off-peak periods in the first stage, airlines then simultaneously and individually determine their aggregate passenger quantities and their peak supply.

The analysis starts with consideration of fixed demand. It shows that there is internalization of self-imposed schedule delay and congestion delay costs by carriers with market power when a competitive fringe is absent, while there is no self-internalization at all when a competitive fringe is present. It is further shown that the peak-toll incorporates a premium that is fully determined by schedule delay cost independent of whether a competitive fringe exists or not. In this case, airport cost recovery (for an arbitrary size of peak capacity) can be achieved if the schedule parameter is sufficiently high relative to average capacity costs.[11]

Morrison (1987), Morrison and Winston (1989) and Pels et al. (2003), among others, showed empirically that business passengers have a greater value of time than leisure passengers. Furthermore, Czerny and Zhang (2011, 2012, 2013), Yuen and Zhang (2011) and Zhang and Czerny (2012) show that carriers′ behaviors and airport congestion charges depend crucially on the differences between the business and leisure passengers′ time valuations in a static environment. Specifically, they show that it is the marginal passengers′ time valuation attached to congestion delays that determines carrier behavior and thus congestion prices. The present paper shows that this changes in the case of a POP environment with schedule delays. Here, the carriers′ internalization of self-imposed schedule delay and congestion delay costs, and therefore the welfare-optimal peak toll structure and airport cost recovery, depend on the time valuation attached to schedule delays of the passenger who is just scheduled for departure during the peak period at the welfare optimum. On the other hand, time valuations attached to congestion delays have no effect on the welfare-optimal peak toll structure simply because there is no congestion in the welfare optimum.[12]

For the case of elastic demands, it is shown that the welfare-optimal peak tolls can achieve the first-best welfare result and airport cost recovery when the schedule parameter is sufficiently high. This is true in spite of the fact that the off-peak period

[5] The bottleneck model with stochastic queues was further used by Daniel and Harback (2008), who considered 27 major US airports and also found that carriers may be treated as atomistic independent of whether a dominant carrier exists or not, and by Daniel and Harback (2009) and Daniel (2011) for the derivation of welfare-optimal airport congestion tolls for US and Canadian airports, respectively.

[6] Vickrey (1969) originally developed the deterministic bottleneck model with fixed demands for the case of roads, where schedule delays costs are linear and increasing in the absolute difference between the most preferred and actual travel times. Daniel and Pahwa (2000) applied the results derived for roads in their airport study. Silva et al. (2013) also adapted the bottleneck approach to the case of airports, but explicitly accounted for the vertical structure between airports and airlines. Furthermore, they incorporate elastic demands in the way developed for roads by Arnott et al. (1993).

[7] Airport congestion pricing with carriers competing in a Bertrand fashion is considered by Silva and Verhoef (2013).

[8] Mayer and Sinai (2003) also provide empirical evidence that supports the finding that carriers internalize self-imposed congestion. Morrison and Winston (2007) find little evidence for self-internalization. Rupp′s (2009) empirical findings on the same issue are mixed. See Zhang and Czerny (2012) for a recent survey paper that discusses airport congestion pricing.

[9] Following Daniel (1995), it is assumed that arrival and departure queues are independent. The analysis can thus concentrate on departures, which is without loss of generality.

[10] As was pointed out by Basso and Zhang (2008) this is not a crucial assumption.

[11] To be precise, average capacity costs refer to capacity costs divided by the peak capacity.

[12] Since passengers see peak-period departures as a “high quality” service relative to off-peak departures, this is consistent with the literature on the firms′ incentives for quality supply (for example, Spence, 1975; Sheshinski, 1976).

consists of a carrier subsidy because the peak-period toll, which is determined by the schedule parameter, is positive and therefore increases revenues.[13]

We further investigate a uniform-toll regime, where the same toll is charged during the peak and off-peak periods. The analysis shows that there are two types of welfare-optimal uniform tolls, which will be referred to as the *high uniform-toll* and the *low uniform-toll*, both of which are strongly related to carrier market power. The high uniform-toll becomes relevant when passengers exhibit a strong preference for peak trip, which means that at the second-best welfare optimum, which is conditional on the uniform toll being charged, all passengers are scheduled for departure during the peak period (this can occur when the schedule parameter is sufficiently high). In this scenario, the welfare-optimal uniform toll consists of a carrier subsidy element and a term that corrects for external schedule delay and congestion delay costs. The low uniform-toll becomes relevant when passengers exhibit a low preference for peak departure, which means that at the second-best welfare optimum passengers are scheduled for departure during both the peak and off-peak periods (this can occur when the schedule parameter is sufficiently low). In this scenario, the welfare-optimal uniform toll consists of a carrier subsidy element only. Furthermore, we find that an increase in carrier market power can lead to an increase in welfare. This is true because an increase in market power increases the incentive for self-internalization and reduces the peak-passenger quantity and congestion in the case of a low uniform-toll. In the case of a high uniform-toll, changes in carrier market power do not change welfare at all. This is because, in this case, congestion costs depend only on the welfare-optimal aggregate passenger quantity, which is independent of carrier market power. This further implies that the "critical" value of the schedule parameter (where the welfare achieved under both the low and the high uniform-toll is the same) increases in carrier market power. Clearly, airport cost recovery may only be achieved under the high-toll regime.

The paper is organized as follows. Section 2 describes the basic model, which involves fixed passenger quantities faced by carriers and a peak airport-toll structure. Section 3 analyzes different carrier market structures including monopoly and oligopolistic carrier market structures as well as the Stackelberg leader/competitive fringe structure. This section also considers an extension of the basic model to multiple passenger types with distinct time valuations for schedule delay and congestion delay costs. The case of elastic trip demands is examined in Section 4. Section 5 concentrates on a uniform-toll structure and uses an example to investigate the relative welfare effects of both the high and low uniform-toll regimes. Section 6 provides conclusions and discusses avenues for future research.

2. Basic model

Our basic model considers n symmetric carriers, each with given passenger quantities denoted as q_i, which gives aggregate passenger quantity $q \equiv nq_i$.[14] There are two periods denoted as $t=p,o$: the passengers' preferred departure time is during period 1, to be referred to as the peak period with $t=p$. Period 2 is called the off-peak period with $t=o$. Gross benefits are the same for all passengers and denoted as μ. All passengers prefer departing during the peak period to departing during the off-peak period in the sense that they experience a cost $\delta(>0)$ when they depart during the off-peak period (i.e., per-passenger benefits of off-peak departures are $\mu-\delta$). The parameter δ can have the interpretation of a "schedule delay" cost (simply called *schedule parameter* in the following), since it determines the passengers' costs when the actual travel time is not within the passengers' most preferred travel time, which is the peak period. In transport economics, schedule delays are typically derived from the absolute difference between the actual and most preferred travel times. In the present paper, the differences between the preferred and actual departure times are not uniquely defined because passengers prefer to travel during peak hours, while they are indifferent with respect to the exact departure time inside the peak period. Similarly, if passengers depart during the off-peak period, then benefits are independent of when departure occurs inside the off-peak period.

The airport capacity during the peak period is limited and given by k.[15] Normalizing the length of the peak period to one and letting T denote the length of the off-peak period, assume that $T>q/k$, which ensures that all passengers could potentially be accommodated during the off-peak period.

Denote carrier i's passenger quantities scheduled for the peak period (called "peak supply") by q_{pi} and the passenger quantities scheduled for the off-peak period (called "off-peak supply") by q_{oi}. The aggregate peak supply is $q_p \equiv \sum_i q_{pi}$, whereas the aggregate off-peak supply is $q_o \equiv \sum_i q_{oi}$ with $\sum_t q_{ti} \equiv q_i$.

If aggregate peak supply is below peak capacity (i.e., $q_p \le k$), there is no congestion because carriers avoid overlap in the scheduled departure times (there is no incentive for overlaps because passengers are indifferent with respect to departure times inside both the peak and off-peak periods). On the other hand, if $q_p > k$, some passengers scheduled for peak departure are diverted to the off-peak period by congestion with (expected) individual delays, denoted as C, with $C \equiv C(q_p)$ and $C=C'=0$ when $q_p \le k$, while $C'>0$ and $C'' \ge 0$ when $q_p>k$, which means that individual delays are a convex function of peak supply.[16] Note that individual delays depend on the peak supply, which means that every passenger scheduled for peak departure causes congestion even though some of these passengers are diverted to the off-peak period.

Without loss of generality, it is further assumed that congestion costs are borne by passengers with positive and uniform time valuations v.[17] Passengers scheduled for peak departure do not know ex ante when they are supposed to depart during the peak period, which means that expected congestion costs are the same for all passengers and given by vC. Total congestion costs can be calculated as $q_p vC$.

A novel feature, that distinguishes the present model from the previous POP models (for example, Brueckner, 2002; Basso and Zhang, 2008), is that it captures the probability that passengers who are scheduled for peak-period departure actually depart during peak hours because of congestion. This probability is denoted as P with $P \equiv P(q_p)$ and may be less than one, which depends on peak supply:

Assumption 1. For passengers who are scheduled for departure during peak hours, it holds that the probability that they actually depart during peak hours is $P(q_p) \equiv \min\{1, k/q_p\}$.

Thus, if the aggregate peak supply is sufficiently small ($q_p \le k$), there is no congestion and all passengers can actually be accommodated during the peak period (that is, $P=1$). If the aggregate peak supply exceeds the peak-period capacity, there is a positive probability (given by $1-P$) that some of these passengers are

[13] That welfare-optimal airport congestion tolls incorporate a subsidy element when carriers have market power has first been pointed out by Pels and Verhoef (2004).

[14] The case of elastic travel demands will be examined in Section 4.

[15] Thus, peak capacity is determined by factors outside of the model.

[16] One way of thinking about how the passengers who are scheduled for peak departure are diverted to the off-peak period is by queuing with the random queue discipline (rather than the first-in-first-out queue discipline). Arnott (2013) uses the random queue discipline for the case of roads.

[17] Since congestion costs are separable from other costs, the assumption that congestion costs are fully borne by passengers (and not by carriers) is without loss of generality.

diverted to the off-peak period because of delays (in this situation, $P' < 0$). However, the aggregate passenger quantity served during the peak period is constant and equal to capacity $q_p P = k$ in this situation ($q_p \geq k$). Assumption 1 further implies that P' is the same for all carriers, which is useful for deriving symmetric solutions.

Altogether there are three groups of passengers: (1) passengers who are scheduled for peak departure and depart during peak hours, (2) passengers who are scheduled for peak departure but depart during off-peak hours, and (3) passengers who are scheduled for off-peak departure. Passengers cannot affect C as individuals are atomistic, and because passengers in the first group experience no schedule delays but congestion, equilibrium prices become $\mu - vC$. Passengers in the second group experience both schedule delays and congestion delays, which means that the benefits become $\mu - \delta - vC$ in this group, while they receive a penalty payment δ by carriers when carriers do not provide the right quality in terms of departure times.[18] All passengers scheduled for peak departure therefore ultimately pay the same price independent of whether they depart during peak or off-peak hours. Passengers in the third group experience schedule delay only and no congestion, which leads to equilibrium prices $\mu - \delta$. Passengers are indifferent between peak and off-peak departures in this scenario.

The airport charges carriers with a per-passenger fee τ_p for departure during the peak period with $\tau_p \leq \delta$ in order to ensure that peak supply is attractive for carriers. In the current setting of given aggregate passenger quantities q_i for each carrier, we can normalize the airport charge for off-peak departures to zero, which is without loss of generality. Other carrier costs are also normalized to zero. Carrier i's expected profit for given quantities of passengers scheduled for peak-period departure can then be written as

$$\pi_i \equiv (\mu - \delta) q_i + ((\delta - \tau_p) P(q_p) - vC(q_p)) q_{pi}. \tag{1}$$

The first term on the RHS of (1) assumes that all passengers are charged with the off-peak fare $\mu - \delta$, but passengers who are scheduled for peak departure and who actually depart during - peak hours (the corresponding quantity can be calculated as $q_{pi}P$) yield extra per-passenger profit $\delta - \tau_p$, which is captured by the second term and becomes zero if $\tau_p = \delta$. Furthermore, all passengers scheduled for peak departure experience congestion costs independent of whether they depart during the peak or the off-peak period, which reduce peak prices and therefore appear as carrier costs given by $q_{pi} vC(q_p)$ in the last term.

Airport profit can be written as

$$\Pi \equiv q_p P \tau_p - \rho, \tag{2}$$

where the second term on the RHS of (2) denotes the airport's capacity costs. Social welfare can then be written as

$$W \equiv \mu q - (q - \min\{k, q_p\})\delta - q_p vC - \rho, \tag{3}$$

where the first term on the RHS of (3) determines the (gross) benefits, the second term captures the schedule delay costs of passengers who depart during off-peak, the third term represents the congestion costs, while the last term are the capacity costs.

Let q_p^* denote the welfare-optimal solution (i.e., $q_p^* = \arg\max_{q_p} W$). Since the passenger quantities are given, total surplus is maximized when the sum of schedule delay and congestion costs are minimized. This holds true when aggregate peak supply is exactly equal to the peak capacity, i.e., $q_p^* = k$, because in this situation peak capacity is fully used and there is no congestion.

We consider a two-stage game: in the first stage, the airport chooses the optimal peak toll τ_p. In the second stage, carriers simultaneously choose the shares of passengers scheduled for departures during the peak period in order to maximize their own profits.

[18] Our main results do not hinge upon this assumption, however.

3. Analysis

The analysis in this section first concentrates on a monopoly carrier and then considers the more general framework of an oligopolistic carrier market. Extensions of the basic model that capture the existence of a Stackelberg leader with a competitive fringe and passenger types with distinct time valuations attached to schedule delays and congestion delays are also considered.

3.1. Monopoly carrier

Consider a monopoly carrier ($n = 1$) with $q_1 > k$.[19] In this case, the carrier profit can be written as

$$\pi_1 = \begin{cases} (\mu - \delta) q_1 + q_{p1}(\delta - \tau_p) & \text{for } q_{p1} < k \\ (\mu - \delta) q_1 + (\delta - \tau_p) k - q_{p1} vC(q_{p1}) & \text{for } q_{p1} \geq k. \end{cases} \tag{4}$$

The monopoly carrier's scheduling behavior in terms of peak supply is determined by the first-order condition $\partial \pi_1 / \partial q_{p1} = 0$. Note that

$$\frac{\partial \pi_1}{\partial q_{p1}} = \begin{cases} \delta - \tau_p & \text{for } q_{p1} < k \\ -vC - q_{p1} vC' & \text{for } q_{p1} \geq k, \end{cases} \tag{5}$$

which is equal to zero only if $q_{p1} = k$, thus implying $q_{p1}^M = k$ (superscript M indicates the monopoly solution). One can easily check that the second-order condition is satisfied for $q_{p1}^M = k$, since $\partial(vC + q_{p1} vC') / \partial q_{p1} > 0$ due to the convexity of delays C.

Thus, there is no need to correct the monopoly carrier's behavior when there is a peak period with limited capacity, since the carrier perfectly internalizes schedule delay and congestion costs and so maximizes welfare. In other words, the monopoly carrier will not schedule an excessively high quantity of passengers for departure during the peak period relative to the peak-period capacity.

To summarize:

Proposition 1. *For a monopoly carrier and given aggregate passenger quantity, any airport charge can implement the welfare-optimal solution, i.e.* $\tau_p^* \leq \delta$ *(where the asterisk indicates the welfare-optimal solution).*

Thus, a zero toll charged to the monopoly carrier during the peak period can implement the welfare-optimal solution, since $\delta > 0$. To ensure airport cost recovery, it may however be useful to consider a positive peak toll, where the maximum revenues conditional on welfare optimality are given by $k\delta$ (when the off-peak toll is zero). It thus holds:

Proposition 2. *The welfare-optimal solution ensures airport cost recovery if the per-passenger schedule delay cost exceeds average capacity costs, i.e.* $\delta \geq \rho / k$, *when there is a monopoly carrier and the passenger quantity is given.*

Altogether, this complements the findings of Silva et al. (2013), who derive monopoly carrier behavior in a deterministic bottleneck framework. Specifically, the contribution is to derive and analyze the first-order condition in (5), which is directly informative with respect to the full range of optimal tolls in the case of a monopoly carrier and to derive conditions for airport-cost recovery when peak capacity is arbitrary in size.

[19] The case of $q_1 \leq k$ is less interesting in our context.

3.2. Oligopolistic carriers

More generally, assume that $n \geq 1$, that is, there can be an oligopolistic carrier market. Consideration of oligopolistic markets is used to analyze the relationship between scheduling behaviors and market shares. For example, it is well known that the incentives to internalize self-imposed congestion are inversely related to market shares when carriers compete in quantities a la Cournot (e.g., Brueckner, 2002; Zhang and Zhang, 2006). The main contribution here is to show that a similar logic can be applied to schedule delays.

To analyze the potential for self-internalization of the congestion *and* schedule delay costs by oligopolistic carriers (when passenger quantities are given in our basic model), assume that $q_i < k$ while $nq_i > k$ for n > 1. Using profits in (1), the carrier behavior is determined by the first-order conditions $\partial \pi_i / \partial q_{pi} = 0$ (noting that the second-order conditions hold; see the discussion in Footnote 20). With symmetry, the first-order conditions reduce to

$$(\delta - \tau_p)P - vC + \frac{1}{n}((\delta - \tau_p)P' - vC')q_p^N = 0, \tag{6}$$

where $i = 1, \ldots, n$ and superscript N indicates the Nash equilibrium solution. In order to derive equilibrium carrier behavior, it is useful to distinguish the two cases where (i) aggregate peak supply may be less than peak capacity in equilibrium (i.e., $q_p^N < k$) and (ii) aggregate peak supply may exceed peak capacity in equilibrium (i.e., $q_p^N \geq k$).

Consider case (i). This implies $P' = C' = C = 0$, which means that the first-order condition in (6) reduces to $\delta - \tau_p = 0$; thus, this is a solution only if $\tau_p = \delta$. On the other hand, if $\tau_p < \delta$, case (i) cannot be an equilibrium solution because the schedule parameter exceeds the peak-charge, which means that an increase in peak supply increases carrier profit.

Now consider the more interesting case (ii), where the peak supply exceeds the peak capacity in equilibrium: using $-q_p P' = P$ and rearranging the terms in (6) leads to[20]

$$(\delta - \tau_p)P - vC - \frac{1}{n}(q_p^N vC' + (\delta - \tau_p)P) = 0. \tag{7}$$

The first two terms give the (expected) extra profit from peak relative to off-peak supply. The last two terms on the LHS are negative and weighted with market shares. The first of these two terms, $q_p^N vC'/n$, determines the internalization of self-imposed congestion, while the second, $(\delta - \tau_p)P/n$, is the novel part discovered by the present analysis. This newly identified part determines the internalization of self-imposed schedule delay costs.

Consider congestion first. The marginal effect of peak passengers on congestion costs is given by the first derivative of congestion costs, $q_p vC$, with respect to peak supply, which yields $vC + q_p vC'$. Note that the first term is internalized by carriers because it determines the extra profit from the peak relative to off-peak supply. The second term also appears on the LHS of (7), but is weighted by market shares $1/n$. Thus carriers increasingly internalize marginal congestion costs when carrier market power rises, as they recognize they impose congestion on themselves. Such internalization reduces equilibrium peak supply relative to an atomistic carrier market with an infinite number of carriers.

Turning now to schedule delays, the marginal effect of peak departures on the aggregate carrier profit is given by the first derivative of the aggregate extra profit from the peak relative to off-peak supply, $(\delta - \tau_p)q_p P$, with respect to peak departures. This derivative can be written as $(\delta - \tau_p)P - (\delta - \tau_p)P = 0$ for $q_p \geq k$ (again, we use the fact that $-q_p P' = P$ in this situation). If $\tau_p = \delta$ this marginal effect clearly is zero; while this marginal effect must also be zero for $\tau_p < \delta$ because an increase in peak supply cannot reduce aggregate schedule delays once peak supply exceeds peak capacity. Furthermore, the first term on the LHS, $(\delta - \tau_p)P$, is fully internalized by carriers because it determines the extra profit from the peak relative to off-peak supply, while the second term on the LHS, $-(\delta - \tau_p)P$, appears on the LHS of (7) weighted with market shares $1/n$. Thus, oligopolistic carriers increasingly internalize the marginal gains in aggregate extra profits, which are zero, when carrier market power rises. The intuition is that carriers recognize that they impose schedule delays on themselves in the sense that an increase in peak supply pushes their own passengers scheduled for peak departure to the off-peak period, and the probability for this to occur depends on market shares.

Altogether, this leads to an interesting difference between the congestion and schedule delay costs: with congestion, carriers may not account for marginal costs that are relevant from the social viewpoint. With schedule delay costs, on the other hand, carriers may account for some reductions in schedule delay costs, which are non-existent from the social viewpoint.

The LHS of (7) is also informative with respect to the welfare-optimal peak toll, which can implement the first-best solution. This toll is essentially the same as the Vickrey-toll (Vickrey, 1969) and equals the schedule delay costs, which are determined by the schedule parameter δ in the present paper. To see this, note that only $\tau_p = \delta$ eliminates the incentives to increase or decrease the peak supply when the peak-period capacity is reached. Thus, the welfare-optimal peak toll is unique and given by $\tau_p^* = \delta$ for all $n \geq 2$. (While $\tau_p^* = \delta$ also is a solution for $n = 1$, it is not the unique solution when $n = 1$.) The intuition is similar as the one for roads: a welfare-optimal peak toll (which is equal to the schedule delay costs) implies that carriers are indifferent between the peak and the off-peak supply when there is no congestion; consequently, it eliminates any incentives for an excessive use of peak capacity because this will impose additional congestion costs. Importantly, this is consistent with the full utilization of peak capacity: since carriers are indifferent between the peak and off-peak departures when $\tau_p = \delta$, one can assume that carriers make a full use of peak capacity. There are however multiple equilibria in this situation, and the under-supply of peak services (i.e., $q_p^N < k$) would also be an equilibrium solution for $\tau_p = \delta$.[21]

Furthermore, this shows that although there is self-internalization of the congestion and schedule delay costs, the welfare-optimal peak toll is not affected by market structure and the existence of self-internalization when $n \geq 2$. The reason is that the welfare-optimal toll eliminates peak-period congestion. If congestion would be present at the optimum, the equilibrium level of congestion and schedule delay costs would clearly depend on market structure, and hence the size of the toll would show this dependence as well. But with no congestion present at the optimum, this dependence is not present.

To summarize:

Proposition 3. *There is internalization of self-imposed costs of both congestion and schedule delay when aggregate passenger quantities are given, which depends on market power in the sense that the internalization of self-imposed delays (whether these are congestion or schedule delays) increases in carrier market power. Still, the welfare-optimal peak toll is independent of carrier market power when carrier markets are oligopolistic and passenger quantities are given.*

[20] One can show that $\partial^2 \pi_i / \partial q_{pi}^2 < 0$ is true for $q_p > k$, and that the slopes of carriers' best-response functions implied by their first-order condition (6) are strictly less than one in absolute values for $\tau_p < \delta$. Taken together, these properties ensure the existence of a unique carrier equilibrium for $\tau_p < \delta$.

[21] A peak charge $\tau_p = \delta - \varepsilon$ with $\varepsilon \to 0$ can ensure that peak capacity is fully used with congestion costs arbitrarily close to zero.

This extends the recent airport congestion literature (which shows that carriers with market power have an incentive to internalize self-imposed congestion costs) to the self-internalization of both the congestion and schedule delay costs. Furthermore, a relevant policy conclusion is that the "atomistic toll," which is given by the welfare-optimal peak toll for an infinite carrier number, implements the first-best solution also when carriers have market power. This directly follows from the fact that the welfare-optimal peak toll is independent of carrier market power when quantities are given.

This further implies:

Corollary 1. *Airport-cost recovery is unaffected by the existence of an oligopolistic market relative to a monopoly situation when aggregate passenger quantities are given.*

3.3. Stackelberg leader with competitive fringe

We now modify the carrier market structure from monopoly/oligopoly to a Stackelberg leader with competitive fringe. As a consequence, the Stackelberg leader (represented by index 0) first chooses its peak supply, q_{p0}, which is followed by the fringe carriers' scheduling of peak departures, q_{pi} for $i>0$, taking the leader's peak supply as given.

To identify the effect of a competitive fringe on the Stackelberg leader's incentives to internalize self-imposed congestion and schedule delay costs, it is sufficient to derive the comparative-static relationships between the fringe carriers' peak supplies and the Stackelberg leader's peak supply, which follows Zhang and Czerny's (2012) approach.[22] Assuming that the fringe carriers' peak supplies are determined by the first-order conditions in (6) with $q_p \equiv \sum_{i=0}^{n} q_{pi}$ (which means that aggregate peak supply is composed of the Stackelberg leader's and the fringe carriers' peak supplies), the comparative-static relationships between the fringe carriers' peak supplies and the Stackelberg leader's peak supply can be derived by totally differentiating this first-order condition with respect to the fringe carriers' peak supplies and the Stackelberg leader's peak supply. Using symmetry, this yields

$$\left(\frac{\partial^2 \pi_i}{\partial q_{pi}^2}+(n-1)\frac{\partial^2 \pi_i}{\partial q_{pi}\partial q_{pj}}\right)dq_{pi}^N+\frac{\partial^2 \pi_i}{\partial q_{pi}\partial q_{p0}}dq_{p0}=0 \tag{8}$$

with $j\neq i$. Since $\partial^2\pi_i/\partial q_{pi}\partial q_{pj}=\partial^2\pi_i/\partial q_{pi}\partial q_{p0}$ for $j\neq i$ and $i=1,\ldots,n$, this leads to

$$\frac{dq_p^N}{dq_{p0}}=-n\frac{\partial^2\pi_i/\partial q_{pi}\partial q_{p0}}{\partial^2\pi_i/\partial q_{pi}^2+(n-1)\partial^2\pi_i/\partial q_{pi}\partial q_{p0}}, \tag{9}$$

where

$$\frac{\partial^2 \pi_i}{\partial q_{pi}^2}=2((\delta-\tau_p)P'-vC')+q_{pi}^N((\delta-\tau_p)P''-vC'') \tag{10}$$

$$\frac{\partial^2 \pi_i}{\partial q_{pi}\partial q_{p0}}=(\delta-\tau_p)P'-vC'+q_{pi}^N((\delta-\tau_p)P''-vC''). \tag{11}$$

This reveals that when there is a competitive fringe (i.e., when $n\to\infty$), the RHS of Eq. (9) approaches -1, which eliminates the Stackelberg leader's incentive for the internalization of self-imposed congestion and schedule delay costs. The optimal (non-discriminating) peak toll, which eliminates the fringe carriers' incentives to move into the peak period and reaches the first-best solution, is therefore $\tau_p^*=\delta$. Thus:

Proposition 4. *If there is a competitive fringe*:

(i) *A Stackelberg-leader will not internalize self-imposed congestion and schedule delay costs.*

(ii) *The unique, non-discriminating welfare-optimal peak toll is unchanged by the existence of a Stackelberg leader relative to an oligopoly situation when aggregate passenger quantities are given.*

This directly implies:

Corollary 2. *Airport-cost recovery is unaffected by the existence of a Stackelberg leader with a competitive fringe relative to a monopoly or an oligopoly situation, respectively, when aggregate passenger quantities are given.*

The non-internalization result is consistent with the findings of Daniel (1995), Brueckner and van Dender (2008) and Silva et al. (2013). Furthermore, if the airport could charge differentiated tolls to the Stackelberg leader and fringe carriers, a positive toll $\tau_p^*=\delta$ could be charged to fringe carriers, while it may be sufficient to charge the Stackelberg leader with a reduced toll that is smaller than the value of the schedule parameter. The reason is that the fringe carriers' toll $\tau_p^*=\delta$ eliminates the fringe carriers' incentives to use the peak period, while the Stackelberg leader may schedule passengers during the peak period but has no incentives to exceed the peak-period capacity and induce congestion because of the internalization of self-imposed schedule delay and congestion costs. This effect has already been pointed out by Silva et al. (2013). It can be easily shown that there is scope for the internalization of self-imposed schedule and congestion delays when carrier services are differentiated (e.g., Brueckner and van Dender, 2008; Zhang and Czerny, 2012; Silva et al., 2013).

3.4. Passenger types

Empirical evidence shows clearly that passenger types with distinct time valuations exist, where time valuations can be associated with schedule or congestion delays. Specifically, the time valuation of business passengers typically exceeds that of leisure passengers.[23] Accordingly, denote the carriers' (given) quantities of business passengers as q_i^B and the corresponding quantities of leisure passengers as q_i^L, with $q_i^B+q_i^L\equiv q_i$. Furthermore, denote the aggregate quantities of business and leisure passengers as q^B and q^L, respectively, with $q^B\equiv nq_i^B$ and $q^L\equiv nq_i^L$.

We start with the consideration of distinct time valuations attached to schedule delays. Assume that, for peak departures relative to off-peak departures, the schedule parameter is δ^B for business passengers and δ^L for leisure passenger with $\delta^L<\delta^B$ and that the time valuations associated with congestion delays are the same for the two passenger types. Assume further that carriers can price discriminate between the two groups, which means that fares for business passengers during the off-peak period become $\mu-\delta^B$ while the corresponding fares for leisure passengers become $\mu-\delta^L$.[24] Letting q_{pi}^B and q_{pi}^L denote, respectively, the business and leisure peak supplies with $q_{pi}^B+q_{pi}^L\equiv q_{pi}$, the expected aggregate peak departures of business and leisure passengers can be calculated as q_p^BP and q_p^LP, respectively. Furthermore, it is useful to denote average schedule delays as $\overline{\delta}_i$ with $\overline{\delta}_i\equiv(q_{pi}^B\delta^B+q_{pi}^L\delta^L)/q_{pi}$.

[22] In contrast to the present paper, Zhang and Czerny (2012) consider a static model of airport congestion.

[23] Business passengers have a greater value of time than leisure passengers (for example, Morrison, 1987; Morrison and Winston, 1989; USDOT, 1997; Pels et al., 2003).

[24] Airport congestion pricing and third-degree airline price discrimination with elastic demands has been considered by Czerny and Zhang (2012) in a static environment.

Expected carrier profits then become

$$\pi_i^s \equiv \mu_i^s + (\overline{\delta}_i - \tau_p) q_{pi} P - q_{pi} vC, \tag{12}$$

where $\mu_i^s \equiv \mu q_i - q_i^L \delta^L - q_i^B \delta^B$ and superscript s indicates the scenario of distinct time valuations for schedule delays.

Airport profits are not directly affected by the changes in this section relative to the basic scenario, since peak charges are uniform over passenger groups. Expected welfare can be written as

$$W^s \equiv \mu^s + (\overline{\delta} P - vC) q_p - \rho, \tag{13}$$

where $\mu^s \equiv n\mu_i^s$ and $\overline{\delta} \equiv (q_p^B \delta^B + q_p^L \delta^L)/q_p$. Business passengers clearly have priority from the social viewpoint, which yields welfare-optimal peak supplies $q_p^{B*} = \min\{k, q^B\}$ and $q_p^{L*} = \max\{0, k - q_p^{B*}\}$.

The carriers' problems are to maximize their profit for the given quantities of business and leisure passengers, which means, again, the minimization of schedule delay and congestion delay costs. Formally, the carriers' maximization problems can be written as

$$\max_{q_{pi}^L, q_{pi}^B} \pi_i^s \quad \text{s.t. } q_{pi}^L \le q_i^L \quad \text{and} \quad q_{pi}^B \le q_i^B. \tag{14}$$

It is useful to distinguish the two cases where (i) the aggregate business-passenger quantity exceeds the peak-period capacity ($q^B > k$), and (ii) the aggregate business-passenger quantity does not exceed the peak-period capacity ($q^B \le k$). Note that $\delta^L < \delta^B$ implies that the marginal carrier profits derived from business peak supply are greater than the corresponding marginal profits derived from leisure peak supply ($\partial \pi_i^s / \partial q_{pi}^L < \partial \pi_i^s / \partial q_{pi}^B$). Thus, if the aggregate business quantity exceeds the peak-period capacity (case (i)), the welfare-optimal peak toll is determined by the peak passengers' schedule parameter in order to eliminate the excessive use of the peak-period capacity. Leisure passengers will not be scheduled for peak-period departure in this situation.

The more interesting case is case (ii). Here, all business passengers are scheduled for peak departure and the carriers decide upon the additional leisure peak supply. In this case, the leisure peak supplies are determined by the first-order conditions $\partial \pi_i^s / \partial q_{pi}^L = 0$, which implies

$$(\delta^L - \tau_p) P - vC - \frac{1}{n}(q_p vC' - q_p(\overline{\delta}_i - \tau_p) P') = 0. \tag{15}$$

The first two terms on the LHS of Eq. (15) give the extra profit from peak relative to off-peak supplies. The subsequent terms show that carriers internalize self-imposed congestion and schedule-delay costs, both of which depend on market shares.

For case (ii), one can show that $\partial^2 \pi_i^s / \partial (q_{pi}^L)^2 < 0$ and that best-responses in terms of the leisure passenger peak supplies have slopes less than one in absolute values when the leisure schedule parameter is sufficiently large.[25] There is thus a unique equilibrium in this situation. Furthermore, since the optimal peak toll eliminates congestion, the first-order condition displayed in (15) directly reveals that the welfare-optimal peak toll is determined by the leisure schedule parameter (i.e., $\tau_p^s = \delta^L$) in case (ii). The discussion therefore leads to:

Proposition 5. *When business passengers attach a high time valuation to schedule delays relative to leisure passengers, the welfare-optimal peak toll is determined by the business passengers' schedule parameter if the aggregate business quantity exceeds the peak-period capacity (i.e., $q_B \ge k$); and it is determined by the leisure passengers' schedule parameter otherwise.*

Since the departure time determines service quality, this result is in line with the results derived by Spence (1975) and Sheshinski (1976), who concentrated on a monopoly firm and found that the firms' quality choices depend on the quality valuation of the marginal customer. In the above case (i), the marginal customer is a business passenger at the welfare-optimum, while the marginal customer in case (ii) is a leisure passenger. Similar results have been derived by Czerny and Zhang (2011, 2013) for the case of airport congestion in a static environment, while Proposition 5 refers to the first-best peak toll in a POP environment.[26]

The implications for airport-cost recovery can be described as:

Corollary 3. *When business passengers attach a high time valuation to schedule delays relative to leisure passengers and the aggregate business quantity exceeds the peak-period capacity, the welfare-optimal peak toll ensures airport-cost recovery if the business schedule parameter exceeds average capacity costs, i.e. $\delta^B \ge \rho/k$; while the leisure schedule parameter must exceed average capacity costs, i.e. $\delta^L \ge \rho/k$, in order to ensure airport-cost recovery otherwise.*

Time valuations can depend on passenger types not only for schedule delays but also for delays caused by congestion. However, since congestion does not exist in the first-best solution, the welfare-optimal peak toll and the corresponding effects on airport-cost recovery are independent of differences in time valuations attached to congestion delays by the business and leisure passengers. Thus, for the derivation of the welfare-optimal peak toll and airport-cost recovery, it is important to recognize the existence of passenger types with distinct time valuations, with the differences with respect to the valuations of schedule delays being of particular importance.

4. Elastic demands

The preceding analysis takes each carrier's aggregate passenger quantity as given. As a consequence, each carrier just decides on peak supply and the airport just needs to decide on a peak toll τ_p. To analyze elastic trip demands, we need to assume that the airport charges an off-peak toll, denoted as τ_o, in addition to τ_p with $\tau_p - \tau_o \le \delta$ in order to ensure that peak supply can be positive in equilibrium. Further, we assume that the (gross) passenger benefits, denoted as B, depend on the aggregate passenger quantity, q, i.e. $B \equiv B(q)$ with $B'' < 0$. As in the basic scenario, passengers prefer peak relative to off-peak departures in the sense that aggregate schedule delay costs are given by $(q - \min\{k, q_p\})\delta$.

Let p_p denote the peak fare and p_o the off-peak fare. The passengers' peak "full-fares" are then composed of the peak price and congestion costs (i.e., the peak full-fares are $p_p + vC$). Again, the peak full-fares are independent of whether passengers scheduled for peak departure depart during the peak period or are diverted to the off-peak period because peak passengers receive a penalty payment δ if they are forced to depart during the off-peak period by congestion. On the other hand, the full fares for off-peak departures are composed of the off-peak fare and schedule delay costs (i.e., the off-peak full-fares are $p_o + \delta$). Consumer surplus can be written as

$$CS^e(q, q_p) \equiv B - (p_p + vC) q_p - (p_o + \delta)(q - q_p), \tag{16}$$

where q_o is substituted by $q - q_p$ and e stands for "elastic." The first term is the gross passenger benefits. The second term is the peak

[25] Specifically, $\delta^L > \tau_p + (\overline{\delta}_i - \tau_p)(1 + 2/q_p)/((1 + 1/q_p)n)$ ensures that $\partial^2 \pi_i^s / \partial q_{pi}^L \partial q_{pj}^L$ is strictly negative in sign.

[26] It is noted that similar results can be derived for the case of horizontal product differentiation. Assume, without loss of generality, that business passengers only travel with carrier 1, while leisure passengers only travel with carrier 2. This is a situation with horizontal product differentiation, which would leave the results described by Proposition 5 unchanged.

full fares multiplied by the aggregate peak supply, while the third term is the corresponding term for off-peak supply.

Since passengers are atomistic, passengers consider average congestion costs *and* the probabilities to depart during peak hours as given. Differentiating the consumer surplus in (16) with respect to aggregate quantities q and peak departures q_p (for given values of P and C), then yields demand equilibrium conditions $p_o = B' - \delta$ and $p_p = B' - vC$. It directly follows that full fares in peak and off-peak periods must be the same in equilibrium (i.e., $p_o + \delta = p_p + vC = B'$), which is intuitive.

Carrier profits can be written as

$$\pi_i^e \equiv B' q_i - (\delta + \tau_o) q_i + ((\delta - (\tau_p - \tau_o))P - vC) q_{pi}. \tag{17}$$

The first term shows carrier revenues when congestion and schedule delay costs would be zero. The second term shows the carrier costs (composed of schedule delay costs and off-peak airport charges) if all passengers are scheduled for off-peak departure, while the final terms describe the profit gains from peak supply (composed of expected reductions in schedule delay costs, congestion costs and expected extra payment for airport infrastructure use during peak hours). We focus on scenarios where the equilibrium passenger quantities are sufficiently high to ensure that some passengers are scheduled for off-peak departure.[27]

Welfare can be written as

$$W^e \equiv CS^e + \sum_i \pi_i^e \tag{18a}$$

$$= B - (q - \min\{k, q_p\})\delta - q_p vC. \tag{18b}$$

Letting superscript "$e*$" indicate the welfare-optimal solution, the welfare-optimal peak supply clearly equals peak capacity (i.e., $q_p^{e*} = k$) and the welfare-optimal aggregate passenger quantity is reached when marginal benefits are equal to the schedule parameter (i.e., the welfare-optimal aggregate passenger quantity is implicitly determined by $B'(q^{e*}) - \delta = 0$ for $q^{e*} > k$).

With elastic demands, carriers individually and simultaneously choose quantities q_i and q_{pi} to maximize their profits (17). To ensure a unique carrier equilibrium (for $\tau_p - \tau_o < \delta$), the following (standard) assumption is made:

Assumption 2. For any $q > 0$, $B'' + qB''' < 0$.

This ensures that carriers' passenger quantities are strategic substitutes and the slopes of the carriers' best-response functions are strictly less than one in absolute values. These, together with the second-order conditions and the fact that scheduling behavior is unaffected by the aggregate passenger quantities as long as some passengers, are scheduled for departure during the off-peak period, ensure the existence of a unique Nash equilibrium of airline rivalry for $\tau_p - \tau_o < \delta$.

To derive the basic intuition, a monopoly carrier ($n=1$) is considered first, again. Monopoly profit can be written as

$$\pi_1^e \equiv \begin{cases} B' q_1 - (\delta + \tau_o) q_1 + (\delta - (\tau_p - \tau_o)) q_{p1} & \text{for } q_{p1} < k \\ B' q_1 - (\delta + \tau_o) q_1 + (\delta - (\tau_p - \tau_o))k - vCq_{p1} & \text{for } q_{p1} \geq k. \end{cases} \tag{19}$$

The carrier's behavior is determined by the first-order conditions $\partial \pi_1^e / \partial q_1 = 0$ and $\partial \pi_1^e / \partial q_{p1} = 0$. Given that $q_{p1} < q_1$ in optimum, the aggregate passenger quantity is determined by

$$B' + B'' q_1^M - (\delta + \tau_o) = 0, \tag{20}$$

which shows that the aggregate passenger quantity is reduced by schedule delay costs relative to a situation with a peak capacity that is sufficiently large to serve the entire demand. The partial derivative with respect to the peak supply is

$$\frac{\partial \pi_1^e}{\partial q_{p1}} = \begin{cases} \delta - (\tau_p - \tau_o) & \text{for } q_{p1} < k \\ -vC - q_{p1} vC' & \text{for } q_{p1} \geq k, \end{cases} \tag{21}$$

where $q_{p1}^M = k$ is a solution as in the previous section with given passenger quantities, since the first-line on the RHS is nonnegative, while the second line is strictly positive for $q_{p1}^M > k$. Again, the monopoly carrier fully internalizes congestion and schedule delay costs.

To derive the welfare-optimal off-peak toll, we use the fact that $B' - \delta = 0$ in the welfare-optimum. The unique welfare-optimal off-peak toll then directly follows from the first-order condition in (20) and is given by $\tau_o^{e*} = B'' q_1^{e*}$. The RHS is clear-cut and negative in sign; the welfare-optimal off-peak toll therefore establishes a carrier subsidy. The welfare-optimal peak-toll is not unique. To see this, recall that the peak capacity should be fully used but without causing any congestion at all. Since $\partial \pi_1^e / \partial q_{p1} \geq 0$ for $q_{p1} \leq k$ when $\tau_p \leq \tau_o + \delta$, while $\partial \pi_1^e / \partial q_{p1} \leq 0$ for all $q_{p1} \geq k$, all $\tau_p \leq \tau_o^e + \delta$ can implement the first-best result. Thus, to implement the welfare-optimal solution, the off-peak toll is used as a subsidy, while the peak toll needs to ensure that the peak capacity is fully used; thus, $\tau_p^{e*} \leq B'' q_1^{e*} + \delta$, where the RHS is positive in sign if the schedule parameter is sufficiently high (i.e., if $\delta > -B'' q_1^{e*}$).

Turning to oligopolistic carrier markets, the carriers' behavior is determined by the first-order conditions $\partial \pi_i^e / \partial q_i = 0$ and $\partial \pi_i^e / \partial q_{pi} = 0$, which can be written as

$$B' + B'' q_i^N - (\delta + \tau_o) = 0 \tag{22}$$

and

$$(\delta - (\tau_p - \tau_o))P - vC - \frac{1}{n}(q_p^N vC' + (\delta - (\tau_p - \tau_o))P) = 0. \tag{23}$$

Since full internalization of schedule delay and congestion delay costs does not occur in this scenario when $n > 1$, the welfare-optimal peak toll structure becomes unique and is given by

$$\tau_o^e = B'' q^{e*}/n \quad \text{and} \quad \tau_p^e = B'' q^{e*}/n + \delta. \tag{24}$$

As in the monopoly case, the aggregate passenger quantities q_i are not determined by the schedule delay and congestion delay costs, while carriers trade-off the expected peak-toll payments against the expected marginal schedule delay and congestion costs when they determine the peak supplies.

This leads to:

Proposition 6. *The welfare-optimal off-peak toll is a subsidy that ensures achievement of the first-best passenger quantity when there is carrier market power, while the welfare-optimal peak toll ensures that peak capacity is fully used but without congestion.*

The result of the welfare-optimal off-peak toll being a subsidy has been shown by Basso and Zhang (2008), but the results on the welfare-optimal peak toll are different between the two studies. While Basso and Zhang found that the peak toll may even be smaller than the off-peak toll, this will not happen in our model. The difference arises largely due to the fact that we consider both the schedule delay and congestion costs while they consider only the congestion cost.

[27] The condition holds when

$$(\delta + \tau_o - B_o')/B_o'' > ((\delta - (\tau_p - \tau_o))P - vC)/(vC' - (\delta - (\tau_p - \tau_o))P') > k/n$$

is satisfied in equilibrium. The first inequality ensures that off-peak supply is positive, while the second inequality ensures that peak supply exceeds peak-period capacity in equilibrium.

The welfare-optimal peak toll structure in (24) implies that airport cost recovery can be achieved when

$$\delta \geq \rho/k - B'' \cdot (q^{e*})^2/(nk). \tag{25}$$

The RHS shows that airport cost recovery may be more likely when carrier competition increases (which is true whether there is a Stackelberg leader or not). This is true because the subsidy element incorporated in the welfare-optimal peak toll structure is reduced by carrier competition, while the peak premium, which is required to achieve the welfare-optimal solution, is independent of the carrier market structure.

Thus[28]:

Proposition 7. *If the schedule parameter is sufficiently high, the welfare-optimal peak toll structure ensures airport cost recovery, while airport cost recovery is easier to achieve if the carrier market is more competitive, which is true in the sense described by the inequality in (25).*

5. Uniform tolls

Airport peak-toll structures can hardly be found in practice (e.g., Schank, 2005). An important variation of the toll structure, which is of high practical importance, is considered in this section. More specifically, a "uniform toll" is considered, where the same toll is charged during both the peak and off-peak periods, i.e., $\tau_p = \tau_o = \tau_u$ (u for "uniform").[29] The carrier profits then become

$$\pi_i^u \equiv (B' - (\delta + \tau_u))q_i + (P\delta - vC)q_{pi}. \tag{26}$$

5.1. Welfare-optimal uniform toll

Consider $n=1$. The previous discussion already showed that the monopoly carrier need not to be incentivized to perfectly internalize schedule delay and congestion costs. In the case of a monopoly carrier, the welfare-maximizing airport must only ensure that the welfare-optimal aggregate quantity is achieved. Recall that the optimal peak toll structure, which implements the first-best solution, is given by (24). It directly follows that the uniform toll $\tau_u = B'' q^{e*}$ can implement the first-best result when a monopoly carrier exists. The optimal uniform-toll structure is more complex when an oligopolistic market structure is considered.

Consider now $n \geq 2$. The carriers' behavior is determined by the first-order conditions $\partial \pi_i^u / \partial q_i = 0$ and $\partial \pi_i^u / \partial q_{pi} = 0$, which lead to a unique carrier equilibrium. It is useful to distinguish between two cases:

(i) $q^u = q_p^u$, and
(ii) $q^u > q_p^u$,

where superscript u indicates the equilibrium solution under uniform tolls.

In case (i), the first-order conditions reduce to

$$B'' q_p^u/n + B' - (1-P)\delta - \tau_u - vC - \frac{1}{n}(q_p^u vC' + P\delta) = 0. \tag{27}$$

The first three terms on the LHS of (27) display marginal revenue, while the rest of the terms display, respectively, the uniform toll, the per-passenger congestion costs, and the part of congestion and schedule delay costs for which internalization depends on market shares. This shows that, in case (i), the aggregate passenger quantity is determined by a trade-off between the marginal revenues and the schedule delay and congestion delay costs.

In case (ii), the first-order conditions that determine the carriers' behaviors $\partial \pi_i^u / \partial q_i = 0$ and $\partial \pi_i^u / \partial q_{pi} = 0$ can be written respectively as

$$B'' q_i^u + B' - \delta - \tau_u = 0 \tag{28}$$

and

$$P\delta - vC - \frac{1}{n}(q_p^u vC' + P\delta) = 0. \tag{29}$$

In this case, (28) implies that the aggregate passenger quantity is independent of schedule delay and congestion delay costs, while the peak passenger quantity is independent of the uniform toll as implied by (29).

One can show that the following lemma, which is useful to identify the welfare-optimal uniform tolls, holds true[30]:

Lemma 1. *(i) The aggregate passenger quantity is decreasing in the uniform toll and the schedule parameter, which is independent of whether off-peak supply is absent or present. (ii) The aggregate peak supply is decreasing in the uniform toll only if off-peak supply is absent in equilibrium, while aggregate peak supply is independent of the uniform toll otherwise. (iii) The aggregate peak supply is increasing in the schedule parameter if off-peak supply is strictly positive.*

Since an increase in the uniform toll increases marginal carrier costs, which is independent of peak and off-peak supply, it is intuitive that the aggregate passenger quantity is decreasing in the uniform toll. Furthermore, an increase in schedule delay costs reduces off-peak demand. Since we concentrate on scenarios where off-peak departures are always present (passengers are scheduled for off-peak departure or they are diverted to the off-peak period by congestion), it is also intuitive that the aggregate passenger quantity is decreasing in the schedule parameter as described in part (i) of Lemma 1. Part (ii) is directly intuitive, since peak supply depends on uniform tolls only if off-peak supply is zero. Finally, since schedule delay costs can be avoided by peak departures relative to off-peak departures, peak departures may be increasing in the schedule parameter, which provides an intuition for part (iii) of Lemma 1.

To derive the welfare-optimal uniform toll, assume that the peak capacity is fully used in equilibrium. Using welfare in (18b), the welfare-optimal uniform toll is determined by the first-order condition $\partial W/\partial q \cdot \partial q/\partial \tau_u + \partial W/\partial q_p \cdot \partial q_p/\partial \tau_u = 0$, which implies

$$(B' - \delta)\frac{\partial q}{\partial \tau_u} - (vC + q_p^{u*} vC')\frac{\partial q_p}{\partial \tau_u} = 0, \tag{30}$$

where superscript "$u*$" indicates the welfare-optimal solution under uniform tolls.

Case (i) implies $\partial q/\partial \tau_u = \partial q_p/\partial \tau_u < 0$ by Lemma 1. In this case, the first-order (30) can be rewritten as

$$B' - \delta = vC + q_p^{u*} vC', \tag{31}$$

which shows that the welfare-optimal uniform toll should equalize the difference between marginal benefits and schedule delay costs and marginal congestion costs. This toll is unique and denoted as $\tau_u(H)$, where H stands for *high* because the toll eliminates the carriers' incentives for off-peak supply (otherwise, case (ii) would be the relevant one). Uniqueness results from the fact that the aggregate passenger quantity is decreasing in the

[28] For the discussion of airport cost recovery in the case of a deterministic bottleneck model, see Silva et al. (2013). For the discussion of cost recovery in the static airport congestion models, see Brueckner (2002) and Zhang and Zhang (2006).

[29] The concept of a uniform toll is common in the context of roads (e.g., Arnott et al., 1993).

[30] Lemma 1 follows almost immediately from Assumption 2, which together with Assumption 1 implies $\partial^2 \pi^i / \partial q_i \partial q_j < 0$ for cases (i) and (ii).

uniform toll, and the LHS of (31) is decreasing in the aggregate passenger quantity, while the RHS of (31) is increasing in peak supply (which is equal to the aggregate passenger quantity in case (i)) by Lemma 1.

Case (ii) implies $\partial q_p/\partial \tau_u = 0$ by Lemma 1. In this case, the first-order condition (30) can be rewritten as

$$B' - \delta = 0, \tag{32}$$

which shows that the uniform toll should be chosen such that the difference between marginal passenger benefits and schedule delay costs equal marginal cost of off-peak passengers, which are normalized to zero. This toll is again unique and denoted as $\tau_u(L)$, where L stands for *low* because the toll ensures that off-peak supply exists (otherwise, case (i) would be the relevant one).

Substituting $vC + q_p vC'$ for $B' - \delta$ and 0 for $B' - \delta$ in the first-order conditions in (27) and (28) respectively, and solving for the welfare-optimal uniform tolls leads to

$$\tau_u(\theta) = \begin{cases} B'' q^{u*}/n & \text{for } \theta = L, \\ B'' q^{u*}/n + P\delta + q_p^{u*} vC' - (q_p^{u*} vC' + P\delta)/n & \text{for } \theta = H, \end{cases} \tag{33}$$

where $\theta = L$ (called the "low-toll regime") implies $q_p^{u*} < q^{u*}$ and $\theta = H$ (called the "high-toll regime") implies $q_p^{u*} = q^{u*}$. Thus, the welfare-optimal uniform toll always incorporates a carrier-subsidy element, $B'' q^{u*}/n$, which depends on carrier market power. It incorporates a second element, $P\delta + q_p^{u*} vC' - (q_p^{u*} vC' + P\delta)/n$, that internalizes the external schedule delay and congestion delay costs only if all passengers are scheduled for peak-period departure, which also depends on carrier market power. However, in both cases the first-best result cannot be achieved (when $n \geq 2$). This is because in case (ii), the use of the peak-period capacity is excessive, while in case (i) the use of the peak-period is also excessive and, in addition, the aggregate passenger quantity is too low from the social viewpoint.

To summarize:

Proposition 8. *The welfare-optimal uniform toll incorporates a carrier-subsidy element, which is independent of whether off-peak supply is absent or present, while it incorporates an element that internalizes the external schedule delay and congestion delay costs only if the off-peak supply is absent in the welfare-optimum. All elements of the welfare-optimal uniform toll depend on carrier market power.*

Clearly, airport cost recovery can only be achieved under the high toll regime.

Although all elements of the welfare-optimal uniform tolls depend on carrier market power, this is not always true for the welfare effect of carrier market power. Specifically, carrier market power has no welfare impact under the high-toll regime. Note that the first-order condition in (31) controls both passenger benefits and congestion delay cost. Furthermore, this trade-off does not depend on carrier market power, since (31) should be satisfied for all $n \geq 2$ when the high-toll regime is considered. This means that welfare is independent of carrier market power under the high-toll regime when $n \geq 2$.

On the other hand, an increase in carrier market power will always increase social welfare under the low-toll regime. To see this, note that the aggregate passenger quantity is independent of carrier market power under the low-toll regime and is determined by $B' - \delta = 0$. On the other hand, the incentive for the internalization of schedule delay and congestion delay costs increases with carrier market power. The following example is used to show that this implies that the equilibrium peak supply decreases in carrier market power (e.g., $n=1$ implies $q_p = k$), which reduces average congestion costs and increases welfare.

5.2. Example

The previous analysis showed that the airport may have to choose between the low- and the high-toll regime. The question is, what are the conditions that favor the use of the low- or high-toll regimes? To show that the high uniform-toll may be preferred from the social viewpoint when the schedule parameter, δ, is sufficiently high, we introduce specific functional forms and consider numerical instances with three and five carriers to demonstrate the welfare effect of carrier market power. More specifically, consider quadratic passenger benefits and linear per-passenger congestion costs, which lead to

$$B = aq - q^2/2 \quad \text{and} \quad C = \max\{0, c(q-k)/k\} \tag{34}$$

with $c < (a-k)/(2v)$ and $c > 0$, where the first inequality ensures that the congestion costs are sufficiently low in the sense that the quantity of passengers scheduled for peak departures can exceed peak capacity under the high-toll regime.

Recall that peak supply is increasing in the schedule parameter under the low-toll regime and decreasing in the schedule parameter under the high-toll regime by Lemma 1. Assume that $\delta \geq \underline{\phi}$ with

$$\underline{\phi} \equiv \frac{vc}{n-1}, \tag{35}$$

which ensures that peak supply exceeds peak capacity under the low-toll regime for $n \geq 2$. Since quantities are increasing when market power decreases, the lower limit, $\underline{\phi}$, is increasing in carrier market power. To further ensure that peak supply exceeds peak capacity under the high-toll regime, it is assumed that $\delta \leq \overline{\phi}$ with

$$\overline{\phi} \equiv a - k - vc. \tag{36}$$

Altogether, $\delta \in [\underline{\phi}, \overline{\phi}]$ with $\overline{\phi} > \underline{\phi} > 0$.

Equilibrium passenger quantities and welfare-optimal uniform tolls are specified in Appendix A. Fig. 1 displays the welfare-optimal high toll (regime $\theta = H$; solid lines) and low toll (regime $\theta = L$; dashed lines) for parameter specifications $a=2$, $k=v=1$, $c=1/2$ and for $n=3$ and $n=5$. This figure shows that the welfare-optimal uniform tolls are always increasing in the schedule delay cost δ, which is intuitive, since an increase in δ increases the carriers' incentives to schedule passengers for departure during the peak period. Furthermore, one can show that in these instances, aggregate passenger quantities are decreasing, while airport profits are increasing in the schedule parameter, which is true for the high- and the low-toll regime.

The associated welfares for regime $\theta = H$ (solid line) and regime $\theta = L$ (dashed lines) for $n=3$ and $n=5$ are displayed in Fig. 2. This shows that the high uniform toll improves welfare relative to the low uniform toll when schedule delay cost is sufficiently high (i.e. for $\delta \gg 0.41$). Fig. 2 further demonstrates

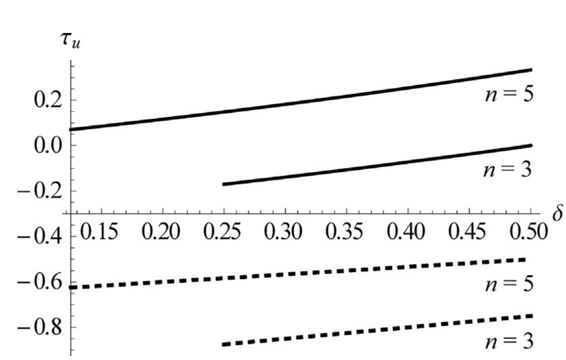

Fig. 1. The welfare-optimal uniform tolls for the relevant ranges of δ under the high-toll regime ($\theta = H$; solid lines) and the low-toll regime ($\theta = L$; dashed lines) for $n=3$, 5. Parameters: $a=2$, $k=v=1$ and $c=1/2$.

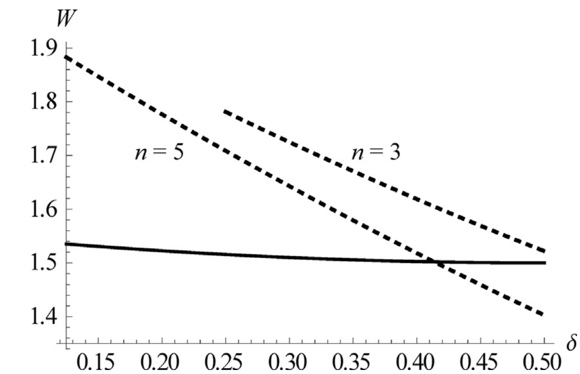

Fig. 2. Welfares under the high-toll regime ($\theta = H$; solid line) and the low-toll regime ($\theta = L$; dashed lines) for the relevant ranges of δ. Parameters: $a=2$, $k=v=1$ and $c=1/2$.

that an increase of carrier market power can improve welfare under the welfare-optimal uniform-toll regime. To see this, observe that welfare is higher when $n=3$ relative to the welfare that exists when $n=5$ under the low-toll regime. This is because carriers′ internalization of self-imposed schedule delay and congestion delay is positively related to carrier market power (Proposition 3).

6. Concluding remarks

This paper has developed an airport POP model that captures the fact that the peak departures cannot exceed the peak-period capacity. The novel feature is that passengers scheduled for peak departure may depart during the off-peak period with some probability (which is decreasing in the aggregate peak supply). This leads to three types of passengers: (1) passengers who are scheduled for peak departure and depart during the peak period, (2) passengers who are scheduled for peak departure but depart during the off-peak period, and (3) passengers who are scheduled for off-peak departure. This framework was used to analyze the carriers′ incentive to internalize self-imposed schedule delay costs in the sense that an increase in peak supply may turn own type-1 passengers into type-2 passengers.

The analysis revealed that there is internalization of both the (self-imposed) schedule delay and congestion delay costs by carriers with market power. Still, the welfare-optimal peak toll structure is of the Vickrey type (i.e. it is determined by schedule delay costs) and independent of carrier market power. It was also shown that the existence of passenger types with distinct time valuations has important implications for the welfare-optimal peak tolls. This is because the carriers′ internalization depends on the time valuation of the passenger who is just scheduled for departure during the peak period.

Our investigation of a uniform-toll regime (where the same toll is charged during peak and off-peak periods) showed that the welfare-optimal uniform toll can be linked to carrier market power in an important fashion. More specifically, the welfare-optimal uniform toll would consist only of a carrier subsidy element when the schedule delay cost is sufficiently low. In that case, an increase in carrier market power improves welfare, since this increases the incentive for self-internalization and reduces the peak-passenger quantity and congestion. On the other hand, if the welfare-optimal uniform toll consists of both a carrier subsidy element and a term that corrects for external schedule delay and congestion costs, then changes in carrier market power do not affect welfare at all.

With respect to airport cost recovery, we derived results for the case of an arbitrary size of the peak capacity. Specifically, we found that airport cost recovery may be easier to achieve if, first, passengers have a strong preference for peak departure and, second, the carrier market becomes more competitive.

This paper has used some simplifying assumptions. First and foremost, the analysis is restricted to two periods in the sense that schedule delay cost can take only two values (zero or a positive constant). The advantage is that this provides an easy-to-handle framework, which can be used to analyze a variety of model extensions, while the main results do not seem to hinge upon this assumption. For example, this is true for the structure of the welfare-optimal peak tolls, which is determined by schedule delay costs,[31] the internalization of self-imposed congestion and schedule delay cost, the role of passengers types, and also the distinction between high and low uniform toll regimes. The latter implies that policy makers have to decide whether they prefer to control congestion or the aggregate passenger quantity. A similar problem would clearly also arise under more general assumptions on the distribution of schedule delay cost as long as off-peak periods with no congestion are present at the airport under consideration. In order to derive practically implementable solutions, more general assumptions on the distribution of schedule delay costs, the stochasticity of demands, etc., would have to be taken into account, while the simplifying approach in the present paper is useful to enhance the transparency of the analysis and to derive clear intuitions.[32]

The paper has also raised a number of avenues for future research. First, a straightforward and important extension of the model developed here is to consider an endogenous peak capacity and to elaborate on the relationship between the revenues raised by the welfare-optimal peak tolls and the costs of building the welfare-optimal capacity. Second, while we have analyzed the properties of both the peak/off-peak and uniform tolls, it is of interest to further explore the magnitude of differences between the two toll regimes in terms of (for example) carrier profits, consumer surplus and social welfare.[33] Third, in our analysis carriers consider airport tolls as given while making their quantity decisions. The case of manipulable tolls along the line of Brueckner and Verhoef (2010) may be further analyzed. Finally, congestion results in costs not only in terms of extra travel time but also in terms of non-reliable travel (see Small, 2012, for a comprehensive recent literature survey), an aspect that is abstracted away from the present paper. Nonetheless, our framework of scheduled peak passengers having probability of actually flying off-peak can be adapted to analyze the reliability issue.

Acknowledgments

We especially thank the editor, Jan Brueckner, and the two anonymous referees for their insightful and constructive comments. We further thank the participants of the Spatial Economics Seminar, Tinbergen Institute, VU University Amsterdam 2012,

[31] Similar results have been derived by Arnott et al. (1993) for the case of roads and Daniel and Pahwa (2000) and Silva et al. (2013) for the case of airports. These authors consider Vickrey-type models where schedule delay costs are linear and increasing in the absolute difference between the most preferred and actual travel times.

[32] See Daniel (1995, 2001, 2011), Daniel and Pahwa (2000) and Daniel and Harback (2008) for an excellent attempt to empirically derive airport congestion tolls for US and Canadian airports.

[33] See Daniel (2001), for an empirical analysis of the distributional consequences of airport congestion pricing, which is based on a bottleneck model with stochastic queues.

Miguel Alcobendas, Eric Pels, Hugo Silva, Ken Small and Erik Verhoef for helpful comments and suggestions.

Appendix A. Example: results

The equilibrium passenger quantities when there are peak and off-peak passengers (regime L) can be derived as

$$q_{oi}(L) = \frac{2an - k\left(\sqrt{(n^2(vc+4\delta)-4\delta)/(vc)}+n\right) - 2n(\tau_u(L)+\delta)}{2bn(n+1)} \tag{37}$$

and

$$q_{pi}(L) = \frac{k\left(\sqrt{(n^2(vc+4\delta)-4\delta)/(vc)}+n\right)}{2n(n+1)} \tag{38}$$

for $\delta \ge \underline{\phi}$, which ensures that $nq_{pi}(L) \ge k$. Furthermore, the equilibrium passenger quantities when there are only peak passengers (regime H, which implies $q_{oi}(H)=0$) can be derived as

$$q_{pi}(H) = \frac{k\sqrt{(n^2(a-\delta+vc-\tau_u(H))^2+4\delta(n^2-1)(k+vc))}+kn(a-\delta+vc-\tau_u(H))}{2n(n+1)(k+vc)} \tag{39}$$

for

$$\delta \le an - k(n+1) - n\tau_u(L) - vc, \tag{40}$$

which ensures that $nq_{pi}(H) \ge k$ (assume equality and solve for δ to derive $\overline{\phi}$).

The airport chooses between uniform tolls $\tau_u(L)$ and $\tau_u(H)$ in the first stage, which can be derived as

$$\tau_u(\theta) = \begin{cases} -(a-\delta)/n & \text{for } \theta = L \\ \Delta/(n(k+2vc)(a+vc-\delta)) & \text{for } \theta = H. \end{cases} \tag{41}$$

with

$$\begin{aligned}\Delta \equiv\ & (a+vc)^2(vc(n-1)-k) \\ & +(k(2a+k(n-1))-2vc((a-2(vc)^2)(n-1)-k(2n-1)))\delta \\ & -(k-vc(n-1))\delta^2.\end{aligned} \tag{42}$$

The associated welfare expressions can be derived by substituting passenger quantities $q_x(\theta)$ with $x \in \{oi, pi\}$ into welfare in (18b).

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