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Liberalization and efficiency in slot-constrained airports

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ABSTRACT

We investigate the presence of inefficiency in slot allocation when an airport allocates slots in destination markets served by monopoly and duopoly airlines, with the number of available peak-time slots constrained by airport capacity. When an airport maintains regulated per-passenger fees, we observe the emergence of allocative inefficiency. Conversely, in scenarios where an airport has the autonomy to set fees, we find that, in line with empirical evidence, fee liberalization resolves these allocative inefficiencies by increasing per-passenger fees. However, the improvement in allocation efficiency may be counterbalanced by the rise in fees, potentially impacting overall welfare.

1. Introduction

In the past decades, the growth in air traffic has outstripped the development of runways and other passenger-handling infrastructure. As a result, many airports are facing critical shortages of infrastructure capacity, particularly during peak periods. Consequently, air transport authorities must be increasingly concerned with the allocation of airport slots (or permits) attributed to airlines for access to the necessary airport infrastructure to depart or land their fleets within specific time frames. A proper evaluation of the industry's conduct regarding slot allocation seems very much welcome.

In addition to that, recent trends in airport regulation are moving towards less governmental involvement. First, many traditionally publicly-owned airports have undergone privatization. Starting with the privatization of airports in the UK in the late 1980s, an increasing number of airports worldwide have been either fully or partially privatized (e.g. Oum et al., 2004, Winston and Ginés, 2009). According to IATA (2017), the share of fully privately-owned airports in Europe increased from 9% to 16% between 2010 and 2016, while the share of mixed ownership models increased from 13% to 25% over the same period.[1] As ownership of airports changes from public to private, the objectives of airports are expected to shift from social benefits to profit maximization.[2]

Second, there are calls for the dismantling of regulations and less stringent price monitoring. As pointed out in ACI (2017), "The role of a regulator and its oversight function is to monitor and ensure that there is no significant abuse of market power. Strict forms of price regulation result in allocative inefficiencies which adversely affect economic incentives." For instance, some airport authorities set a ceiling on the increase in passenger revenues obtained from basic airport services.[3]

In this context, the most relevant regulatory aspect is the management of per-passenger fees. Indeed, in recent years, airports' income has been derived mainly from passenger charges (e.g., passenger service charges, security, and transfer charges), rather than from charges levied directly on aircraft operators (ICAO, 2013).[4] In Europe, for example, airport passenger charges, paid on the average airfare to fly from European airports, more than doubled between 2006 and 2016 (ICAO, 2013; IATA, 2017). Given the growing importance of per-passenger

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[1] Worldwide, among the 100 busiest airports for passengers throughout, 46% have private sector participation. And 41% of global airport traffic is handled by airports that are managed and/or financed by private stakeholders (IATA, 2017).

[2] In addition, many public airports are self-financed and operated under binding budget constraints, which entices them to implement profit-oriented activities.

[3] This then defines the maximum annual revenue per passenger for each year in the regulatory period (e.g., Airports Regulation Document 2017-2021, 2017).

[4] The passenger-based revenues represent 63% of total aeronautical income according to ICAO (2013). In this regard, see Zhang (2012) and Czerny et al. (2017) for discussions about airport improvement fees, which are used to charge passengers for airport infrastructure development and/or debt repayment, and are becoming an increasingly important source of revenue for airports.

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revenue, the analysis of the impact of liberalization on this revenue in the overall airport slot strategy seems highly policy-relevant.

The purpose of this paper is to study the slot allocation problem in a setting where airport authorities liberalize passenger charges. The key assumption is that an airport generates per-passenger revenue, reflecting real-world practices.[5] The paper highlights the economic mechanism by which per-passenger charges affect passenger demands and therefore the airport's flow of passengers during peak and off-peak periods. When airports are concerned with such flows, they are enticed to organize aircraft movements that better meet their objectives. This mechanism results in a quantitative relationship between passenger charges and slot allocation. Importantly, the paper further explores the endogenous determination of airport passenger charges and its impact on slot allocation in the context of airport liberalization. Those effects are plausible not only for the charges that are directly related to the use of slots (e.g. runway, terminal) but also those related to the number of passengers using airport services (e.g. security screening, check-in kiosks). Our paper provides the first discussion of the relationship between airport charges per passenger, peak/off-peak slot allocation, aircraft size and fare prices.

Although this theoretical relationship is novel in the airline economic literature and has not been subject to empirical research, its components are supported by empirical evidence. Indeed, Gillen et al. (2007) show the significant impact of fare prices on passenger demand. Puller et al. (2009) show that on-peak flights are associated with higher fares. Gayle and Lin (2021) estimate how airlines pass on their cost changes to consumers. Avcı and Ates (2022) demonstrate the impact of slot allocation on market concentration, which affects passenger tickets. Although the latter is not directly related to slot allocation, they affect passenger demand and thus airport flows.

Traditionally, airports imposed a single uniform Departing Passenger Charge (DPC) payable by the airline, perceived to cover the cost of providing terminal services.[6] Airport liberalization raises questions about the size and effects of markups that unregulated airports impose on passengers above their costs.

In our framework, a capacity-constrained airport serves destinations with monopoly and duopoly airlines, and establishes its slot allocation as discussed in Picard et al. (2019). Consistent with empirical evidence,[7] there exists a slot allocation inefficiency in which some peak slots are withheld by the airport. When competing airlines set their aircraft seat capacity, they may turn out to carry more passengers if they are allocated on separate time slots, a result that is reminiscent to the maximum product differentiation principle. Importantly, this paper extends the analysis to the scenario where the airport is "unregulated", that is, free to set per-passenger fees without any regulatory constraint, and is served by both airlines on monopoly and duopoly destinations.[8]

Our findings show that the allocative inefficiency arising from unused peak slots may vanish in an unregulated private airport. The airport markup on its services to passengers puts downward pressure on the slot allocative efficiency. Interestingly, the unregulated private airport would never set per-passenger fees so low as to induce slot inefficiency. These results are consistent with empirical regularities. For instance, Bel and Fageda (2010) find that airports controlled by private companies that are not subject to regulation set higher prices than regulated airports.

Next, the paper examines the welfare implications of liberalizing per-passenger fees, which is the main novelty. As mentioned above, liberalization eliminates allocation inefficiency and thus has a positive impact on welfare. In contrast, increasing per-passenger fees reduces the surplus of passengers for a given slot allocation. It follows that if profit-maximizing per-passenger fees are too high, the negative effect on welfare may offset the positive effect of slot reallocation. In this scenario, reservations against the liberalization of charges remain, even if the use of resources becomes more efficient.

In what follows, we abstract away from the practice of airport-slot grandfathering. The way in which we model slot allocation is close to the practice of quantity-based airport management as described for example by Brueckner (2009), where the airport authority allocates a number of slots through free distribution or auction.[9]

To simplify the discussion, our analysis also abstracts from the existence of airport revenues generated by ancillary services offered to passengers (e.g. shopping, parking, etc.). Indeed, public authorities usually do not monitor airports' mark-ups on these services. However, our results on allocative efficiency would hold even if the airport were to set optimal mark-ups on these services. This is because the airport's choice of mark-up is independent of slot management.

Related literature. The present study, to the best of our knowledge, is the first to combine the analysis of slots and pricing policies, making it relevant to both literature.

In the literature on slot allocation and usage, Picard et al. (2019) and Barbot (2004) model different slot periods as vertically differentiated products of high or low quality, allowing airlines to determine their number of flights. Verhoef (2008) and Brueckner (2009) evaluate the effect of adopting slot allocation compared to the alternative policy of congestion pricing. Both contributions show that slot trading, slot auctioning, and first-best congestion pricing result in the same level of passenger volume and welfare.[10] Unlike the present contribution, they do not consider the allocation of slots by the airport without charges. Basso and Zhang (2010) generalize Verhoef (2008) and Brueckner (2009) by introducing airport profits into the analysis, revealing different outcomes with the adoption of slot allocation or congestion pricing. As in this literature, this paper concentrates on vertical differentiation and oligopolistic airline market structures. Li et al. (2010) consider a regulator who aims to maximize social welfare by optimizing the allocation of additional routes to competing carriers. In their model, airlines compete on flight frequency and airfare, and passengers minimize their own travel disutility. Similar to the present paper, they also consider slot allocation in a liberalizing (airline) market, with the aim of guiding the design of related public policies. In two loosely related papers, Kösters et al. (2023) study slot hoarding behavior of airlines in a setting where a monopolistic airline chooses between long-haul and short-haul flights at a slot-coordinated airport. Lang and Czerny (2023) compare decentralized slot and pricing policies when airports are substitutes for

5 Airports are allowed to levy a uniform per-passenger fee for flight activities. With regard to passenger service charges, ICAO (2012) recommends that "these (passenger service) charges should be collected through the aircraft operators where practicable."

6 The charge covers all the terminal infrastructure, the provision of check-in desks, the baggage system, and security screening. The DPC can be split into separate charges for passengers (mainly basic infrastructure and security screening), a fee per bag, rental of the check-in desk, self-service check-in kiosks, etc. All these charges are levied on the airline.

7 See, among others, Zografos et al. (2013), Katsaros and Psaraki (2012) and Airports Council International Europe (2009).

8 Throughout this paper, we will use the term *regulated* to refer to the case where passenger-based airport revenues is exogenously determined by policymakers throughout, and *unregulated* to the case where this revenue is determined by the airport.

9 Citing Brueckner (2009): "Under the quantity-based approaches, the airport authority announces a desired total volume of flights, which is enforced by allocating a corresponding number of airport slots. Under a slot-distribution regime, the slot allocation is achieved by distributing the fixed total number of slots free of charge, while allowing air carriers to adjust their slot holdings through trading. This regime closely corresponds to the slot system in existence at slot-controlled US airports prior to the latest FAA proposals, where trading takes place on secondary markets."

10 In a more recent paper, Lee et al. (2024) discuss an auction-based airport slot reallocation scheme that takes into account the grandfather rights of airlines.

non-local passengers. These two papers discuss airport slot policy with a different focus.

The literature on airport pricing policies is extensive. Notable contributions, such as Ivaldi et al. (2015) and Martín and Socorro (2009), assume that airports negotiate prices with airlines and charge them for the use of aeronautical facilities and passengers through non-aeronautical facility prices. Lin and Zhang (2017) assume that private airports impose per-flight charges on hub carriers for either movement-related or weight-related services and per-passenger charges to maximize profits. Czerny (2013) assumes that in the area of aeronautical services, the airport is a monopoly provider charging a price per passenger to airlines. More recently, Lin (2023) investigates the pricing regime choices between per-flight and/or per-passenger charges for international airports. Yimga (2023) empirically studies the effect of a regulatory change in takeoff and landing restrictions on airfares. However, these papers do not explore the interplay between optimal choice of per-passenger charges and slot allocation.

The paper finally relates to the operational research literature on airport slot management. In contrast to our stylized economic framework, this literature adopts a more practice-oriented approach to numerically assess and optimize airport management procedures using specific airport data. For instance, Adler et al. (2014) model air transport liberalization between airlines and high-speed railways for the Northeast Asian transport market. Focusing on optimal slot allocation, Ribeiro et al. (2018) develop a multi-objective priority-based slot allocation model to optimize slot allocation procedures based on IATA requirements. Ribeiro et al. (2019) adapt the previous framework to the procedures of Level 3 airports to assess whether changes in the global slot guidelines bring benefits to the allocation process. Birolini et al. (2023) study airport slot allocation procedures that maximize available itineraries and minimize connecting times for passengers in Lisbon and Singapore Changi airports. The virtue of this literature is that it encompasses very detailed and specific information on flights, airlines, and airports and optimizes flight allocations under the existing procedures. By contrast, our aim is to shed light on the economic forces behind the slot allocation procedures chosen by airlines and airports and provide an analytical discussion of the long-run welfare effects of airport slot management.

The remainder of this paper is organized as follows. The baseline model is presented in Section 2, while the passenger and airline choices are outlined in Section 3. Slot allocation is discussed in Section 4 and airport liberalization in Section 5. A welfare appraisal is developed in Section 6. Section 7 extends the model and results in a numerical example mimicking the LAX airport. Section 8 discusses the possibility of multiple passenger fees. Section 9 sets forth the conclusion.

2. The model

We study an airport that provides a continuum of destinations with an exogenous mass M served by a single airline (monopolies) and a continuum of destinations with an exogenous mass N served by two airlines (duopolies). Each flight needs one departure slot to operate, so the airport has to allocate a total of $M + 2N$ slots. Each destination has a market size of z passengers, $z \in [\underline{z}, \overline{z}]$. Market sizes of monopoly destinations are distributed with c.d.f. F and p.d.f. $f > 0$; those of duopoly market destinations with c.d.f. G and p.d.f. $g > 0$. Accordingly, the mass of destinations with size dz is given by $Mf(z)\mathrm{d}z$ and $Ng(z)\mathrm{d}z$ in the monopoly and duopoly destinations, respectively.

Destinations are assumed to be independent, implying that the demand for one destination is unrelated to the demand for other destinations.[11] The departure time serves as the only quality dimension perceived by passengers.[12] We consider two travel periods, denoted by i: off-peak ($i = 0$) and peak ($i = 1$). A peak period consists of the most desirable travel times in a day, whilst an off-peak period contains all the remaining time intervals. Examples of peak periods are 7:00-9:00 a.m. for a morning peak and 5:00-7:00 p.m. for an afternoon peak. The peak and off-peak times capacities are denoted as K and L. We consider that the peak period can be running at full capacity while, as at many airports, off-peak period capacity is unconstrained and accommodates the movements of all monopoly destinations and the double movements in all duopoly destinations.[13] This means that $K < M + 2N < L$.

The airport sorts the departure slots to each destination market, either at a peak or off-peak slot. Once the slots have been assigned, the monopoly and duopoly airlines choose their numbers of seats in each destination market. In practice, those numbers of seats correspond to aircraft sizes.[14] An airline's profit in airport pair z is given by $\pi(z) = [p(z) - \phi]\, q(z)$, where $p(z)$ is the airfare, $q(z)$ is the number of seats and ϕ is a per-passenger fee paid to the airport. We simplify the exposition by setting variable operating costs to zero.[15]

Travel services are vertically differentiated by travel time, so that, for a given price, all passengers exhibit a preference for the peak hour. Each passenger is distinguished by her peak-travel taste $v \in [0, 1]$, with v being uniformly distributed with density 1. Passengers evaluate the convenience of a time period based on values vs_0 and vs_1, where s_0 and s_1 are intrinsic value parameters for off-peak and peak departure times, respectively ($0 < s_0 < s_1$). For simplicity, we assume that each passenger flies at most once to a destination and has zero reservation utility. Consequently, passengers are endowed with the utility function, $U_i(v, p_i(z)) = vs_i - p_i(z)$ where $p_i(z)$ is the ticket price to destination z with $i = 1$ if flying at peak time or $i = 0$ if flying at off-peak time.

The airport manages the slot allocation and its activity is rewarded by passenger fee, $\phi \geq 0$. Passenger fees may be collected directly from the passengers or as a charge on aircraft movements which are proportional to aircraft sizes, i.e. the number of passengers. We consider regulated and unregulated airports. For this purpose, we consider that regulation carries over passenger fees so that an unregulated airport is authorized to set its passenger charges. For simplicity, we assume that the airport and the airlines operate under constant returns to scale.

The timing is illustrated in Fig. 1. In the first stage, the unregulated airport sets its preferred per-passenger fees. If the airport is regulated, the fee is exogenously given by the regulation authority. In the second stage, the airport allocates peak and off-peak slots to the airlines, one slot for each airline. A sequential relationship between these two operations reflects the fact that, while slot allocation is determined on a daily basis, per passenger fees are generally pre-set for a certain time period.[16] In the third stage, if a destination is served by a single airline, the monopoly operator sets its seat supply (i.e., aircraft size)

[11] We make an additional assumption that the allocation decisions made by the originating airport do not affect the scheduling of flights at the destination airports. Moreover, our primary emphasis is on outbound flights. For return trip flights, they can be handled by either conducting a parallel analysis involving two runways or by introducing a scale factor, especially in the case of a single runway.

[12] Although various factors contribute to an airline's overall quality, this approach enables us to focus specifically on the peak capacity issue.

[13] Evidence of unconstrained slots during off-peak times can be found, among others, in Barnhart et al. (2012) for Newark Airport (EWR), Swaroop et al. (2012) for several American airports, and Dray (2020) in a study of airports worldwide.

[14] The choice of the number of seats or passengers is a prevalent concept in the airline economics literature. For instance, Pels and Verhoef (2004) explore competition in "passengers", while Brueckner (2009) investigates competition in "flight volume". On the empirical side, Brander and Zhang (1990) show that the competition between duopoly airlines aligns with Cournot behavior.

[15] Variable costs are equivalent to parallel shifts in demand functions. Non-zero variable costs are discussed by Basso and Zhang (2008), Brueckner and Van Dender (2008), and Pels and Verhoef (2004), among others. Section 7 extends the model to non-zero variable costs.

[16] As there is no strategic interaction between the first and second stages, the results do not change if the airport choices are simultaneous. In practice, landing charges are included in airport charge schedules which are updated annually. Airports such as Paris-Charles de Gaulle, San Francisco International Airport and Frankfurt International Airport update their fee schedules, which

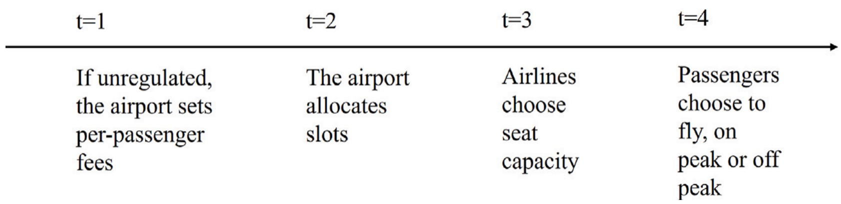

Fig. 1. Timing.

based on the slot allocation. If two airlines serve a destination, they non-cooperatively choose their seat supply based on the slot allocation. Finally, passengers choose to travel, purchase flight tickets, and pursue their travel. The equilibrium concept is subgame perfect Nash equilibrium.

We solve the game by backward induction, beginning by determining the passenger and airline choices, then discuss the slot allocation choice, and finally the per-passenger fee choice of an unregulated airport.

3. Passenger and airline choices

In this section, we examine passenger seat demand and airline seat supply. As destinations are independent for both travelers and airlines, travel demand and airline decisions can be studied separately for each market. Therefore, we analyze destinations served by monopolies and duopolies separately.

3.1. Monopoly destination markets

We identify each monopoly airline by its market size z and time period $i \in \{0, 1\}$. In a destination served by a monopoly, passengers choose to travel only if $s_i v - p$ is greater than their zero reservation utility. Given the uniform distribution of v, a passenger with taste parameter v is willing to fly if

$$v > v_i = \frac{p}{s_i}. \tag{1}$$

Given the above preference, at a price $p_i(z)$, the mass of passengers choosing to travel is equal to $q_i(z) = z\left[1 - p_i(z)/s_i\right]$. The inverse demand function is therefore $p_i(q, z) = (1 - q/z)\, s_i$ and, the monopoly airline's profit is $\pi_i(q, z) = \left[p_i(q, z) - \phi\right] q$. It can readily be shown that the profit maximizing number of seats is equal to $q_i(z) = zq_i$ where

$$q_i = \frac{s_i - \phi}{2s_i}. \tag{2}$$

Because $q_1 > q_0$, the number of passengers is larger at peak time. The resulting travel prices are equal to $p_i(z) = p_i = \left(s_i + \phi\right)/2$, which are also larger at peak time. The optimal monopoly profit $\pi_i(z) = z\left(s_i - \phi\right)^2 / \left(4s_i\right)$ is positive for any slot under the assumption $\phi \leq s_0$.

3.2. Duopoly destination markets

Duopoly airlines engage in seat capacity competition, leading to a Cournot-Nash equilibrium (see Picard et al., 2019). Let us consider two airlines, a and b, flying to the same destination with a market size of z. For conciseness, we dispense with reference to market size z when it does not lead to confusion.

Same time slot. Consider that the two airlines a and b supply q^a and q^b seats in each flight departing at the same slot $i \in \{0, 1\}$. Passengers choose to travel only if $s_i v - p \geq 0$. The total travel demand is thus given by $q = z\left(1 - p/s_i\right)$. This gives the inverse demand function $p\left(q^a, q^b; z\right) = s_i\left[1 - \left(q^a + q^b\right)/z\right]$. Airline a's profits is given by $\pi^a = \left[p\left(q^a, q^b; z\right) - \phi\right] q^a(z)$ while airline b's profit has a symmetric expression. In a Cournot-Nash equilibrium, each airline chooses the number of seats that maximizes its profit, taking as given the competitor's seat capacity. After establishing and solving the first order conditions, one obtains the equilibrium seat capacities $q^a(z) = q^b(z) = zq_{ii}$, where

$$q_{ii} \equiv \frac{s_i - \phi}{3s_i}, \tag{3}$$

and where the double subscript $ii \in \{00, 11\}$, indicates whether the two airlines fly during off-peak (00) or peak (11) periods respectively (we use double subscripts for duopoly destinations). Seat supply naturally varies proportionally with the market size, z, and decreases with the passenger fee. Seat supply and profits are positive under the above assumption of a sufficiently low passenger fee, $\phi \leq s_0$. The equilibrium prices are equal to $p^a(z) = p^b(z) = p_{ii}$ where $p_{ii} \equiv \left(s_i + 2\phi\right)/3$. Since the passenger fee is a cost to the airlines, prices are increasing functions of ϕ.

Different time slots. Consider now that airlines a and b supply q^a and q^b seats in flights departing in the off-peak and peak slot respectively. In the equilibrium, there exist two ticket prices p^a and p^b such that passengers choose to fly in the peak and off-peak periods. Let us assume without loss of generality that flight a uses the off-peak slot. The passenger indifferent between flying and staying has a taste parameter given by $v^a = p^a/s_0$. The passenger indifferent between flying on-peak and off-peak has a taste parameter given by $v^b = \left(p^b - p^a\right)/\left(s_1 - s_0\right)$. Therefore, the demand for off-peak and on-peak flights is equal to $q^b = z(1 - v^b)$ and $q^a = z(v^b - v^a)$. Substituting the previous values into these expressions gives the inverse demand functions $p^a\left(q^a, q^b\right) = s_0\left[1 - \left(q^a + q^b\right)/z\right]$ and $p^b\left(q^a, q^b\right) = s_1\left[1 - \left(q^a s_0/s_1 + q^b\right)/z\right]$, which gives the profits $\pi^a = \left[p^a\left(q^a, q^b\right) - \phi\right] q^a$ and $\pi^b = \left[p^b\left(q^a, q^b\right) - \phi\right] q^b$. In a Cournot-Nash equilibrium, each airline chooses the aircraft seat capacity that maximizes its profit, taking as given the seat capacity of its competitor. Establishing and solving the first order conditions yields the equilibrium seat capacities $q^a(z) = z\, q_{01}$ and $q^b(z) = z\, q_{10}$ where

$$q_{01} \equiv \frac{s_0 s_1 - \phi\left(2s_1 - s_0\right)}{(4s_1 - s_0)s_0} \text{ and } q_{10} \equiv \frac{2s_1 - s_0 - \phi}{4s_1 - s_0}, \tag{4}$$

where the double subscripts 01 and 10 denote the respective airlines in off-peak and on-peak periods respectively. Again, seat capacity increases linearly with market size z. As it can be seen that $q_{01} < q_{10}$, off-peak flights supply fewer seats than peak ones. Off-peak flights also have lower price-cost margins and are therefore less profitable. To ensure positive seat supply and profits, we assume the condition $\phi < \overline{\phi}$ where

$$\overline{\phi} \equiv \frac{s_0 s_1}{2s_1 - s_0}. \tag{5}$$

The seat supply of the above slot configurations is ranked as follows: $q_{10} > q_{11} > q_{00} > q_{01}$. Peak flights carry more passengers than

include landing fees, on an annual basis. Others, such as Marseille Airport and Bremen Airport, only update their fee schedules when significant changes are made, which is much less frequently than annually.

off-peak flights; this difference is more pronounced when airlines are allocated to different travel periods. Furthermore, one can check that more passengers fly when airlines do not simultaneously fly in the off-peak: $q_{01}+q_{10}>2q_{00}$. Importantly, the model predicts that *more passengers fly with duopoly airlines departing on separate slots if passenger fees are sufficiently low*. Formally, we have

$$q_{01}+q_{10}\geq 2q_{11}\iff \phi\leq\hat{\phi}, \tag{6}$$

where

$$\hat{\phi}\equiv\frac{s_0s_1}{2\left(3s_1-s_0\right)}<\overline{\phi}. \tag{7}$$

Intuitively, when moving from the configuration with two peak slots to the one with two different slots, the on-peak airline b raises its fare by a smaller amount than the off-peak airline a drops its fare.[17] As a result, airline b can attract a large share of the former passengers of airline a while the latter is also able to attract a large share of low-value passengers who did not travel before. In the end, more passengers travel to this destination. However, higher passenger fees ϕ mitigate this effect. Indeed, although higher fees raise both airlines' costs, they entice the on-peak airline b to raise its price faster than the off-peak one.[18] As a result, the on-peak airline b is not able not attract a large share of the former passenger base of airline a. One can finally check that, under the last condition, duopoly airlines serve more passengers than monopolies for given z ($2q_{11}>q_1$ and $q_{01}+q_{10}>q_1$).

4. Slot allocation

At the slot allocation stage, the airport's problem is to assign monopoly and duopoly aircraft movements to peak or off-peak slots.

We associate each monopoly destination with market size z with the index $m_0(z)=1$ to monopoly airlines using an off-peak slot and $m_1(z)=1$ to those using a peak time slot ($m_0(z)+m_1(z)=1$). Similarly, we associate a duopoly destination of market size z with the index $n_{11}(z)$ if the two airlines take the peak slot, $n_{01}(z)$ if one airline takes the peak slot and the other does not, and $n_{00}(z)$ if the two airlines take the off-peak slot ($n_{00}(z)+n_{01}(z)+n_{11}(z)=1$). For the sake of conciseness, we dispense the reader with references to specific market size z and support $[\underline{z},\bar{z}]$ whenever it does not create ambiguity.

The airport maximizes its profit subject to its peak capacity constraint. It chooses the sets of slot allocation functions $n=(n_{00},n_{01},n_{11})$ and $m=(m_0,m_1)$ that maximizes profits

$$\begin{aligned}\Pi=\phi\int z\left(q_0m_0+q_1m_1\right)M\,\mathrm{d}F\\ +\phi\int z\left[2q_{00}n_{00}+(q_{01}+q_{10})n_{01}+2q_{11}n_{11}\right]N\,\mathrm{d}G,\end{aligned} \tag{8}$$

subject to

$$\int m_1M\,\mathrm{d}F+\int\left(n_{01}+2n_{11}\right)N\,\mathrm{d}G\leq K, \tag{9}$$

$$m_0+m_1=1, \tag{10}$$

$$n_{00}+n_{01}+n_{11}=1. \tag{11}$$

Replacing m_0 and n_0 from (10) and (11), we can write the Lagrangian function as

$$\begin{aligned}\mathcal{L}=\int\{\ &z\phi\left[q_0\left(1-m_1\right)+q_1m_1\right]Mf-\mu m_1Mf\\ &+z\phi\left[2q_{00}\left(1-n_{01}-n_{11}\right)+(q_{01}+q_{10})n_{01}+2q_{11}n_{11}\right]Ng\\ &-\mu\left(n_{01}+2n_{11}\right)Ng\}\ \mathrm{d}z\ +\mu K,\end{aligned} \tag{12}$$

[17] It can be shown that $p^b-p_{11}=-\left(p^a-p_{11}\right)/2>0$.

[18] The cost pass-through of airline b is greater than that of airline a. Indeed, $dp^b/d\phi=\left(3s_1-s_0\right)/\left(4s_1-s_0\right)>dp^a/d\phi=2s_1/\left(4s_1-s_0\right)>0$.

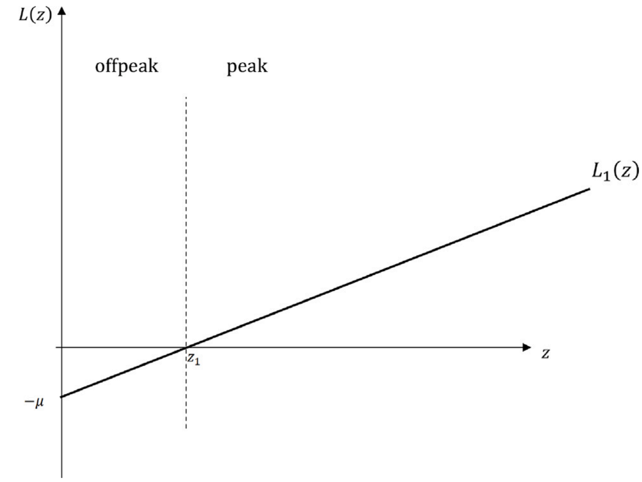

Fig. 2. Marginal profits by monopoly destinations.

where $\mu\geq 0$ is the Kuhn–Tucker multiplier associated with the peak capacity constraint, reflecting the shadow capacity constraint, or equivalently, the marginal profit of a marginal increase in airport capacity. This approach extends Picard et al. (2019) to a mix of monopoly and duopoly destinations.

Pointwise differentiating the Lagrangian function (12) with respect to $m_1(\cdot)$, one readily finds the marginal profit for setting monopoly destinations z on the peak slot

$$\mathcal{L}_1(z)\equiv\frac{\partial\mathcal{L}}{\partial m_1}=\phi\left[z\left(q_1-q_0\right)-\mu\right]Mf. \tag{13}$$

This marginal profit $\mathcal{L}_1(z)$ increases in z and has a root ($\mathcal{L}_1(z)=0$) at

$$z_1\equiv\frac{\mu}{q_1-q_0}=\frac{2\mu\left(s_0s_1\right)}{\phi(s_1-s_0)}. \tag{14}$$

As a result, movements in monopoly destinations are put on peak if $z\geq z_1$ and off-peak otherwise. Fig. 2 depicts the slot allocation for monopoly destinations according to marginal profits, where z represents the size of the destination market. The airport allocates peak slots to destination markets z that provide the highest marginal profits. In particular, it puts the monopoly flights at the peak for each destination market with size $\mathcal{L}_1(z)\geq 0$, i.e. with $z\geq z_1$, and off the peak for each destination market with size $\mathcal{L}_1(z)<0$ $\left(z\in\left(0,z_1\right)\right)$.

Further pointwise differentiation with respect to $n_{01}(\cdot)$ and $n_{11}(\cdot)$ gives the marginal profits for different slots and for the same peak slots in the duopoly airline destination with market size z. That is,

$$\mathcal{L}_{01}(z)\equiv\frac{\partial\mathcal{L}}{\partial n_{01}}=\phi\left[z\left(q_{01}+q_{10}-2q_{00}\right)-\mu\right]Ng, \tag{15}$$

$$\mathcal{L}_{11}(z)\equiv\frac{\partial\mathcal{L}}{\partial n_{11}}=\phi\left[z\left(2q_{11}-2q_{00}\right)-2\mu\right]Ng. \tag{16}$$

As a result, the airport has an incentive to put the two airlines on the same peak slot if $\mathcal{L}_{11}(z)\geq\max\{\mathcal{L}_{01}(z),0\}$, on two different slots if $\mathcal{L}_{01}(z)\geq\max\{\mathcal{L}_{11}(z),0\}$ and on the same off-peak slot if $0\geq\max\{\mathcal{L}_{01}(z),\mathcal{L}_{11}(z)\}$. The marginal profits $\mathcal{L}_{01}(z)$ and $\mathcal{L}_{11}(z)$ are increasing functions of z with intercepts at $-\mu$ and -2μ. They respectively accept positive roots at:

$$z_{01}\equiv\frac{\mu}{q_{01}+q_{10}-2q_{00}}=\frac{3\mu s_0\left(4s_1-s_0\right)}{\left(s_1-s_0\right)\left(s_0+2\phi\right)}, \tag{17}$$

$$z_{11}\equiv\frac{\mu}{q_{11}-q_{00}}=\mu\frac{3s_0s_1}{\phi\left(s_1-s_0\right)}. \tag{18}$$

One can note that the configuration of the slot allocation depends on the level of per-passenger fee. More specifically, if $\phi\in[0,\hat{\phi})$ ("small passenger fees"), the slope of $\mathcal{L}_{01}(z)$ is greater than of that $\mathcal{L}_{11}(z)$ and

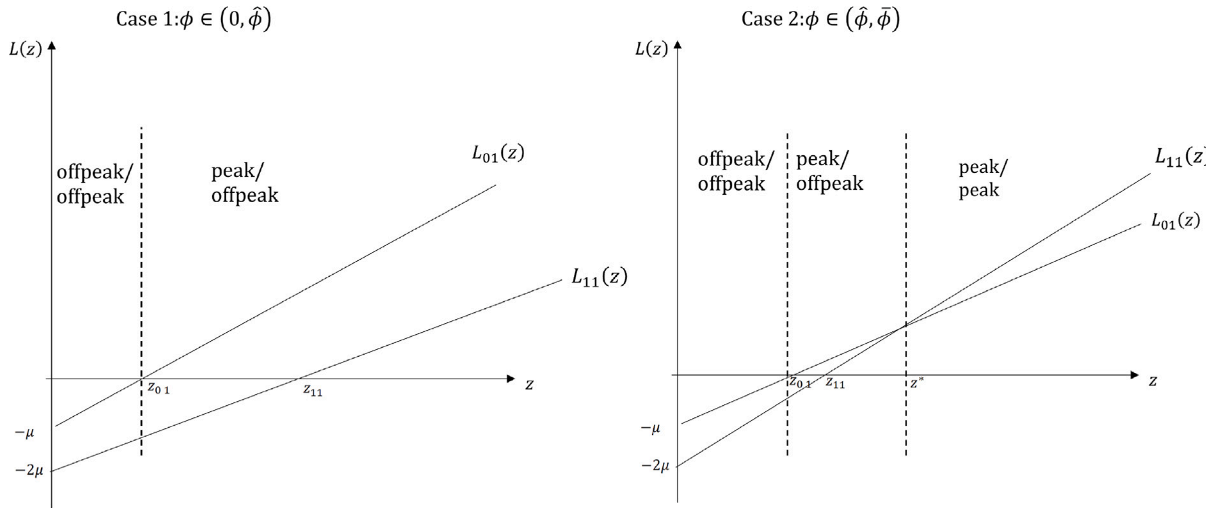

Fig. 3. Marginal profits by duopoly destinations.

the root z_{01} is less than z_{11}. In this case, $\mathcal{L}_{01}(z) > \mathcal{L}_{11}(z)$ for all $z > 0$. The opposite is true for $\phi \in \left[\hat{\phi}, \overline{\phi}\right)$ ("large passenger fees").

It is convenient to study the slot allocation choice according to the level of per-passenger fees. Fig. 3 shows the differences in terms of marginal benefits according to the two regimes. It illustrates the marginal benefits for passengers from destination markets served by duopolies according to whether $\phi \in \left[0, \hat{\phi}\right)$ and $\phi \in \left[\hat{\phi}, \overline{\phi}\right]$.

Similar to what happens for monopoly destinations, the airport sorts peak slots according to the market size of the destination. He places the two duopoly flights on the peak if $\mathcal{L}_{11}(z) \geq \max\left\{\mathcal{L}_{10}(z), 0\right\}$, and assigns only one duopoly flight on the peak if $\mathcal{L}_{01}(z) \geq \max\left\{\mathcal{L}_{11}(z), 0\right\}$. As illustrated in Fig. 3, it becomes apparent that, with small fees $\left(\phi \in \left[0, \hat{\phi}\right)\right)$, duopolies that adopt peak/off-peak slot configurations consistently accommodate a larger number of passengers than peak monopolies. In contrast, when facing high fees $\left(\phi \in \left[\hat{\phi}, \overline{\phi}\right]\right)$, the optimal configuration for maximizing profits depends on the market size. Larger duopoly markets, for instance, are assigned two peak slots, leading to the highest passenger count.

In the sequel, we provide a detailed discussion of the slot allocation for low and high fees separately. As will be seen, although the airport has incentives to fill all peak slots with monopoly destinations, it also has incentives to separate the duopoly destination flights on different time periods to increase total passenger flows when fees are small enough. This raises the possibility of *slot allocative inefficiency,* where the airport does not use all available peak-time slots. This is the key property that we study in this paper and define as follows:

Definition 1. Slot allocative inefficiency occurs when the airport leaves at least one available departure slot unused at peak times.

Small passenger fees. For $\phi \in \left(0, \hat{\phi}\right)$, the airport's marginal profit $\mathcal{L}_{01}(z)$ is always greater than $\mathcal{L}_{11}(z)$. This means that the airport will never choose to put both duopoly airlines on the peak slot. Rather, duopoly airlines are put both on-peak and off-peak ($n_{11}(z) = 0$, $n_{01}(z) = 1$) if $z > z_{01}$ and off-peak and off-peak ($n_{11}(z) = n_{01}(z) = 0$) otherwise.

Let us consider the case where some slots are unused because the capacity constraint is not met. That is,

$$M\left[1 - F(z_1)\right] + N\left[1 - G(z_{01})\right] < K \text{ and } \mu = 0. \tag{19}$$

Since the multiplier is $\mu = 0$, the thresholds z_1 and z_{01} are also zero, making the values of c.d.f. $F(z_1)$ and $G(z_{01})$ null. This implies $M + N < K$. In other words, each destination can be assigned *a single* peak slot. Under this condition, the airport has an incentive to "accentuate" discrimination in duopoly airline destinations and restrict one flight to peak time. This results implies stronger passenger discrimination in destination markets served by two airlines. When the airport allocates an airline to an off-peak slot, it is because the latter sets a very low off-peak fare, leading to an increase in total passenger demand for this destination. The existence of unused peak slots results in *slot allocative inefficiency*, where there are empty peak slots available for a second duopoly flight. This condition does not depend on the market size distributions F and G across monopoly and duopoly destination structures.

By contrast, if $M + N \geq K$, the airport capacity is too small to allocate a peak slot to every destination. The above constraint is binding, and $\mu > 0$. There is no allocative inefficiency in this case. Furthermore, as the airport capacity K decreases, the shadow cost of the capacity constraint μ increases, causing both z_1 and z_{01} to increase. As a result, the airport reduces both the number of monopoly and duopoly destinations on the peak slot.

Large passenger fee. When passenger fees are set to $\phi \in \left[\hat{\phi}, \overline{\phi}\right)$, the airport adopts a richer slot allocation for duopoly airlines. The marginal profit $\mathcal{L}_{01}(z)$ and $\mathcal{L}_{11}(z)$ intersects at

$$z^* \equiv \frac{\mu}{2q_{11} - q_{01} - q_{10}} = \mu \frac{3s_0 s_1\left(4s_1 - s_0\right)}{2\left(s_1 - s_0\right)\left(3s_1 - s_0\right)\left(\phi - \hat{\phi}\right)}, \tag{20}$$

where it can be shown that $z^* \geq z_{01}$ for any $\phi \in [\hat{\phi}, \bar{\phi}]$. This means that duopoly airlines are set off the peak for $z < z_{01}$ because both $\mathcal{L}_{01}(z)$ and $\mathcal{L}_{11}(z)$ are negative; then, the airlines are placed in different slots for $z \in [z_{01}, z^*]$ because $\mathcal{L}_{01}(z)$ is positive and larger than $\mathcal{L}_{11}(z)$; finally, both airlines are placed in peak slots for $z > z^*$ as $\mathcal{L}_{11}(z)$ is positive and larger than $\mathcal{L}_{01}(z)$. As all slots are used, there is *no slot allocation inefficiency* for a large enough passenger fee, $\phi > \hat{\phi}$.

We summarize the above analysis in the following proposition:

Proposition 1. *For any passenger fees $\phi < \hat{\phi}$, the slot allocation is inefficient if $M + N < K$.*

This proposition highlights the significance of the regulator's policy regarding passenger fees in the allocation of airport slots. Setting a low fee incentivizes airports to inefficiently utilize their peak slots and intensify discrimination among passengers. The question at hand is whether this characteristic persists when the airport has the autonomy to determine its own fee.

5. Unregulated airport

For several decades, airport management has experienced waves of liberalization and privatization. Airports in Australia and New Zealand are privately owned, and many European airports operate under a mix of public and private ownership. Numerous regulatory constraints on their revenue-generating activities have been relaxed.

This section develops the main novelty of the paper by analyzing airports that are not regulated and have the authority to set their passenger fees. Our analysis demonstrates that airports attempt to establish passenger fees that deter the adoption of an inefficient slot allocation.

The airport makes profits out of the revenues from the passenger fees. Accordingly, the airport chooses the level of per-passenger fees ϕ that maximizes its profit $\Pi(m^*, n^*, \phi)$, where the slot allocation functions m^* and n^* are the optimal allocations as derived in the previous section.

The optimal fee is given by the following first-order condition:

$$\frac{\partial \Pi(m^*, n^*, \phi)}{\partial \phi} = 0. \tag{21}$$

Because the seat numbers q_i and q_{ij}, $i, j \in \{0, 1\}$, are linearly decreasing functions of ϕ, the function $\Pi(m^*, n^*, \phi)$ is also a linearly decreasing function with $\phi < \hat{\phi}$ and $\phi \geq \hat{\phi}$. Condition (21) determines at most one maximum on each regime. We show below that the first regime accepts no interior maximum and therefore the global maximum lies in the second regime.

Can the airport choose an inefficient slot allocation? We have shown that this situation occurs if the passenger fee is smaller than $\hat{\phi}$. In this case, the airport will never allocate two flights at peak time to the same destination ($n^*_{11} = 0$). The answer is no, as outlined in the next proposition.

Proposition 2. *In an unregulated airport with a mix of monopoly and duopoly destinations, the equilibrium passenger fee ϕ^* exists and is never lower than $\hat{\phi}$. Hence, slot allocation is always efficient.*

Proof. See Appendix. ■

Proposition 2 implies that equilibrium passenger fees are larger than $\hat{\phi}$. The striking consequence of Proposition 2 is the elimination of allocative inefficiency once the airport gains the right to set its passenger fee. The intuition is as follows: if a regulated airport is assigned a low fee by the regulatory authority, then in the slot allocation process it will choose to leave some peak slots unused to encourage duopoly airlines to attract a larger number of passengers during the off-peak period. This is natural: since the fee remains constant for both low and high-valuation passengers, the airport prefers to increase passenger numbers, even if this strategy results in unused slots. If the airport is not confronted with a fee regulation, it can manipulate the fees to render the given schedule suboptimal. Consequently, by excluding the peak/off-peak allocative schedules for each destination, allocative inefficiency is also precluded.

The optimal fee can be characterized as follows. For the sake of clarity, let us redefine the seat numbers q_i and q_{ij} as the linear functions $q_i = q_i^o + q_i'\phi$ and $q_{ij} = q_{ij}^o + q_{ij}'\phi$ where q_i^o and q_{ij}^o are positive intercepts while q_i' and q_{ij}' are negative slopes (scalars). Then, it can be seen that, for any regime, condition (21) yields a unique and positive optimal fee given by

$$\phi^* = -\frac{1}{2}\frac{\left[\begin{array}{c}\int z\left(q_0^o m_0^* + q_1^o m_1^*\right) M\,\mathrm{d}F \\ +\int z\left[2q_{00}^o n_{00}^* + (q_{01}^o + q_{10}^o)n_{01}^* + 2q_{11}^o n_{11}^*\right] N\,\mathrm{d}G\end{array}\right]}{\left[\begin{array}{c}\int z\left(q_0' m_0^* + q_1' m_1^*\right) M\,\mathrm{d}F \\ +\int z\left[2q_{00}' n_{00}^* + (q_{01}' + q_{10}')n_{01}^* + 2q_{11}' n_{11}^*\right] N\,\mathrm{d}G\end{array}\right]} > 0, \tag{22}$$

which is a function of the chosen slot allocation (m^*, n^*) for $\phi > \hat{\phi}$. Given that the slot allocation m^* and n^* are functions of $(z_1, z_{01}, z_{11}, z^*)$, which are themselves functions of ϕ^*, this identity defines a fixed point for the optimal fee ϕ^*. The latter does not accept a generic closed-form solution. To gain analytical insight into the properties of the optimal fees, in this section we break down this study for the special cases of monopoly and duopoly airlines.

5.1. Analysis of optimal fees

The following proposition shows the equilibrium fees when all airlines are monopolies. For convenience, denote as

$$L^m(x) = \int^{F^{-1}(x)} z\mathrm{d}F(z) \Big/ \int z\mathrm{d}F(z), \tag{23}$$

the share of passenger demand below the percentile x of its maximal demand.

Proposition 3. *Suppose an airport that is unregulated and serves all monopoly airlines. Then, the optimal passenger fee is given by:*

$$\phi_M^* = \frac{1}{2}\left[\frac{1}{s_1} + \left(\frac{1}{s_0} - \frac{1}{s_1}\right) L^m(1 - K/M)\right]^{-1}, \tag{24}$$

where $\phi_M^* > \hat{\phi}$.

Proof. In Appendix. ■

Proposition 3 allows us to discuss the behavior of the optimal fees when all destinations are served by monopolies. The passenger fee increases with the expansion of the airport capacity (larger K), because the airport can accommodate more flights during the peak period when each airline attracts more passengers. Conversely, the fee decreases with an increase in the number of destinations (larger M) because the airport includes more off-peak flights with lower passenger loads, resulting in lower airport revenues. If the slot capacity equals the number of destinations, the airport is not capacity constrained and sets its passenger fee to $s_1/2$, which is half of the gross passenger surplus from flying at peak times. If slot capacity is close to zero, and all aircraft fly off the peak, the per-passenger fee is equal to $s_0/2$, which is half of the same surplus during the off-peak times. These values reflect the surplus sharing (double marginalization) in the business chain of the airport and airline monopolies.[19]

We now turn to the analysis in which the airport serves only duopoly destination markets. The optimal fee is obtained in a similar way as for monopolies but is cumbersome to display (see Appendix). Nevertheless, for analytical tractability, we can assume that the destination markets are uniformly distributed: $G : [0, 1] \to 1$, $G(z) = z$. The following proposition holds.

Proposition 4. *Suppose an airport is unregulated and serves only duopoly airlines. Then, the optimal per-passenger fee is given by:*

$$\phi_D^* = \frac{1}{4}\frac{2\left(\frac{4}{s_0} - \frac{1}{s_1}\right)^2 - \left(\frac{1}{s_0} - \frac{1}{s_1}\right)\left(\frac{2}{s_0} - \frac{1}{s_1}\right)\left(2 - \frac{K}{N}\right)^2}{\frac{1}{s_1}\left(\frac{4}{s_0} - \frac{1}{s_1}\right)^2 + \frac{1}{s_0}\left(\frac{1}{s_0} - \frac{1}{s_1}\right)\left(\frac{3}{s_0} - \frac{1}{s_1}\right)\left(2 - \frac{K}{N}\right)^2}, \tag{25}$$

where $\phi_D^* > \hat{\phi}$. It is smaller than $\overline{\phi}$ if $s_1 \leq 3s_0/2$.

Proof. In Appendix. ■

A quick glance at Proposition 4 reveals that ϕ_D^* decreases with $2 - K/N$. Therefore, it decreases with the number of duopoly destinations and increases with the airport's capacity. A larger slot capacity allows the airport to accommodate more airlines during peak slots, increasing passenger demand and, consequently, airport revenues. As the number of destinations increases for the same capacity, the number

[19] Finally, this fee is admissible only if monopoly airlines survive in the off-peak market, i.e., if $\phi^* < s_0$. That occurs if

$$\frac{s_1 - 2s_0}{2s_1 - 2s_0} < L^m(1 - K/M).$$

This condition imposes a lower boundary on M. If off-peak flights are rare, they are obliged to pay the high fee that corresponds to peak flights and therefore cannot survive. The condition nevertheless holds if $s_1 < s_0/2$.

of passengers flying during off-peak times rises, implying lower demand and a lower price. Furthermore, it can be readily checked that a proportional increase in s_0 and s_1 (by the same multiplier m) increases ϕ^*_D proportionally (by m). It can be shown that an increase of s_1/s_0 also increases the fee ϕ^*_D (see Appendix).

6. Welfare

In this section, we assess the social welfare impact of liberalizing per-passenger fees. Following the IO literature, the social welfare function is defined as the sum of passengers' net surplus and airport's and airlines' profits. Passengers' net surplus is measured by the sum of passengers' gross surplus from traveling minus the sum of their fares. Furthermore, given the above assumptions of zero airport and airline operating costs, airport profit is given by total per-passenger fees and airline profits result from travel fares minus per-passenger fees paid to the airport. Monetary transfers between airlines and airports cancel out, as do transfers between passengers and airlines. As a result, *social welfare equals the sum of passengers' gross surplus* in all destination markets.[20] For the sake of clarity, we split the social welfare W into two parts as:

$$W = W^M + W^N, \tag{26}$$

with

$$W^M \equiv \int \left(\sum_i w_i(z) m_i(z) \right) M \mathrm{d}F(z) \quad \text{and } W^N \equiv \int \left(\sum_{ij} w_{ij}(z) n_{ij}(z) \right) N \mathrm{d}G(z),$$

where $w_i(z)$ and $w_{ij}(z)$ are the gross surpluses for monopoly and duopoly destination market with size z and time slots (i, j), respectively, while $m_i(z)$ and $n_{ij}(z)$ denote the above slot allocation choices for this destination market.

We first analyze the airport with only monopolies ($W^N = 0$) and then with only duopolies ($W^M = 0$) in all destination markets, respectively. In Section 7, we will investigate the effects of the liberalization of an airport serving both monopolies and duopolies using a numerical simulation.

6.1. Monopoly destinations

When a monopoly airline with destination market size z is given time slot i, its flight generates a gross surplus

$$w_i(z) \equiv z \int_{1-q_i}^{1} v s_i \mathrm{d}v. \tag{27}$$

Hence, $w_i(z)$ measures the social welfare generated in this destination and time. It can readily be shown that $w_i(z) = z w_i$ where

$$w_i = \frac{(s_i - \phi)(3s_i + \phi)}{8s_i}, \tag{28}$$

which decreases with a higher passenger fee since $\mathrm{d}w_i/\mathrm{d}\phi = -\left(\phi + s_i\right) / \left(4s_i\right) < 0$.

For capacity unconstrained airports ($M \le K$), all flights are at the peak and social welfare is given by the total gross surplus $W_1^M = M \int_0^\infty z w_1 \mathrm{d}G(z)$, which also falls in ϕ. For capacity constrained airports ($M > K$), only flights with destinations $z > z_1$ fly at the peak and social welfare is given by

$$W_0^M = M \int_{z_1}^{\infty} z w_1 \mathrm{d}F(z) + M \int_0^{z_1} z w_0 \mathrm{d}F(z), \tag{29}$$

where both integrands are functions of w_1 and w_0, each falling in ϕ. By contrast, because z_1 satisfies the capacity constraint $M\left(1 - F\left(z_1\right)\right) = K$, it is independent of ϕ. As a result, social welfare always decreases with higher ϕ, regardless of the capacity level.

Proposition 5. *Social welfare decreases with higher passenger fees ϕ at an airport serving a set of monopoly destination markets.*

The implication of Proposition 5 is that, for a given slot allocation, social welfare increases with a decrease in per-passenger fees ϕ.

6.2. Duopoly destinations

If the airport assigns two airlines to a destination market z for the same type of time slot $i \in \{0, 1\}$, each flight generates a gross surplus of $w_{ii}(z) \equiv \frac{1}{2} z \int_{1-2q_{ii}}^{1} v s_i dv$. Conversely, if the airport assigns each duopoly airline to a different time slot, the off-peak flight generates a gross surplus equal to $w_{01}(z) \equiv z \int_{1-q_{01}-q_{10}}^{1-q_{10}} v s_0 dv$ while the peak flight yields $w_{10}(z) \equiv z \int_{1-q_{10}}^{1} v s_1 dv$. Similar to the monopoly analysis, the welfare value of a flight with a destination market size z is given by $w_{ij}(z) = z w_{ij}$, where

$$w_{ii} = \frac{(s_i - \phi)(2s_i + \phi)}{9s_i}, \tag{30}$$

for two flights in the same time period $i \in \{0, 1\}$, and

$$w_{01} = \frac{\left[s_1(s_0 - 2\phi) + s_0\phi\right]\left[3s_1 s_0 + \phi\left(2s_1 + s_0\right)\right]}{2s_0\left(4s_1 - s_0\right)^2}, \tag{31}$$

$$w_{10} = \frac{s_1(2s_1 - s_0 - \phi)(6s_1 - s_0 + \phi)}{2\left(4s_1 - s_0\right)^2}, \tag{32}$$

for two flights in different time periods. We have $dw_{ii}/d\phi < 0$ while $dw_{01}/d\phi < 0$, $dw_{10}/d\phi < 0$ and $d\left(w_{01} + w_{10}\right)/d\phi < 0$.

For small enough fees $\phi < \hat{\phi}$, social welfare is rewritten as

$$W_{01}^N(\phi) = \int_{z_{01}}^{\infty} z(w_{01} + w_{10}) N \mathrm{d}G(z) + \int_0^{z_{01}} z(2w_{00}) N \mathrm{d}G(z), \tag{33}$$

where z_{01} is the equilibrium value that depends on μ given by the capacity constraint $K \ge \int_{z_{01}}^{\infty} N \mathrm{d}G(z)$.

For a larger fee ϕ, which increases above $\hat{\phi}$, z^* decreases from infinite value and social welfare becomes

$$W_{11}^N(\phi) = \int_{z^*}^{\infty} z(2w_{11}) N \mathrm{d}G(z) + \int_{z_{01}}^{z^*} z(w_{01} + w_{10}) N \mathrm{d}G(z) + \int_0^{z_{01}} z(2w_{00}) N \mathrm{d}G(z), \tag{34}$$

where z_{01} and z^* are equilibrium values and depend on μ given by $K \ge \int_{z^*}^{\infty} 2N \mathrm{d}G(z) + \int_{z_{01}}^{z^*} zN \mathrm{d}G(z)$.

We first shed light on the fact that the airport uses peak slots inefficiently if the capacity allows one peak slot at each destination ($M + N < K$) and the passenger fee ϕ is exogenous $\phi < \hat{\phi}$. What is thus the welfare benefit resulting from imposing the airport to allocate duopoly airlines with destination market sizes $z \in [z^*, \infty)$ in the same peak slot? Denoting the initial threshold as z'_{01} and the final ones as z_{01} and z^*, the welfare difference is given by

$$W_{11}^N - W_{01}^N = \int_{z^*}^{\infty} z(2w_{11} - w_{01} - w_{10}) N \mathrm{d}G(z) - \int_{z'_{01}}^{z_{01}} z(w_{01} + w_{10} - 2w_{00}) N \mathrm{d}G(z), \tag{35}$$

where all terms in brackets are positive. The first integral expresses the benefit for the passengers flying on the new peak/peak destinations. The second integral expresses the welfare loss for the passengers obliged to move onto off-peak time. In the case of unused peak slots and allocative inefficiency ($\mu = 0$), the welfare benefit is definitively positive because z'_{01} and z_{01} are both equal to zero. Otherwise, welfare improvement depends on the above balance.

[20] In the Appendix, we provide details on the level of social welfare by airline market.

Second, we study the impact of liberalizing the fee ϕ. We do this by allowing the airport to choose the allocation of slots for a given fee. Consider the case where $\phi < \widehat{\phi}$. The welfare change due to a marginal increase in ϕ is equal to

$$\frac{\mathrm{d}W_{01}^N}{\mathrm{d}\phi} = \int_{z_{01}}^{\infty} z\frac{\mathrm{d}(w_{01}+w_{10})}{\mathrm{d}\phi} N\mathrm{d}G(z) + \int_0^{z_{01}} 2z\frac{\mathrm{d}w_{00}}{\mathrm{d}\phi} N\mathrm{d}G(z) - \frac{\mathrm{d}z_{01}}{\mathrm{d}\phi} z_{01}\left(w_{01}+w_{10}-2w_{00}\right) N g(z_{01}), \tag{36}$$

where the first two terms have negative integrand and the bracket in the third term is positive. We have

$$\frac{\mathrm{d}z_{01}}{\mathrm{d}\phi} = \frac{\mathrm{d}}{\mathrm{d}\phi}\left(\frac{\mu}{q_{01}+q_{10}-2q_{00}}\right) = \frac{\mathrm{d}}{\mathrm{d}\phi}\left(\frac{3\mu s_0\left(4s_1-s_0\right)}{\left(2\phi+s_0\right)\left(s_1-s_0\right)}\right). \tag{37}$$

On the one hand, if the slot capacity is slack, then we have $\mu = 0$ so that $dz_{01}/d\phi = 0$ and $dW_{01}^N(\phi)/d\phi < 0$. Although a higher fee mitigates the slot allocation inefficiency, social welfare falls with higher passenger fees. On the other hand, if the slot capacity binds such that $K = \int_{z_{01}}^{\infty} N\mathrm{d}G(z)$, it is clear that z_{01} is independent of ϕ. So, $dz_{01}/d\phi = 0$ and therefore $d\ W_{01}^N/d\phi < 0$. To sum up, $dW_{01}^N(\phi)/d\phi < 0$ for any $\phi < \widehat{\phi}$. Hence the regulator has no incentive to set small fees. Secondly, in the case where $\phi > \widehat{\phi}$, it can be shown that welfare also decreases with higher fees (see Appendix).

Proposition 6. *In an airport serving a set of duopoly destination markets, welfare decreases with higher ϕ if $\phi \neq \widehat{\phi}$. For uniform G, it has a positive jump at $\phi = \widehat{\phi}$.*

Proof. See Appendix. ■

The second part of the proposition is proved by assuming a uniform distribution, and this jump is further confirmed in the numerical simulation which is devoted to the study of the general case with monopolies and duopolies (see Section 7). Intuitively, welfare improvement arises from resolving allocative inefficiency. This is evidenced by the absence of a jump in the welfare analysis when the airport serves only monopolies; indeed, in that situation, no allocative inefficiency occurs.

The proposition implies that an increase in passenger fees may improve welfare if it encourages the airport to reallocate duopoly flights to peak slots when the fee reaches $\widehat{\phi}$. This result can be explained by noting the increase in competition when the airport sets peak/peak or off-peak/off-peak duopolies rather than peak/off-peak duopolies. Indeed, with only one peak time per destination offered, passengers benefit from relatively lower prices, irrespective of the departure hour.

However, once reallocation has taken place, social welfare falls again as per-passenger fees increase. It follows that liberalization has a positive effect on social welfare only if the optimal airport choice is not too far from the threshold $\widehat{\phi}$. Otherwise, the negative effect of higher fees would more than offset the positive effect of reallocation.

When we consider destinations served by both monopolies and duopolies, analytical tractability precludes us from deriving clear-cut analytical welfare comparison. In the next section, we cover this aspect by developing a numerical example consistent with the findings obtained analytically in the rest of the paper.

7. Numerical example

In this section, we develop a numerical example that is consistent with the findings obtained analytically in the rest of the paper and is consistent with existing airport operations. To this end, we generalize our model by including airline and airport variable costs per passenger, c and k, and a demand shifter u such that $U_i = u + s_i v - p_i$. The shifter u reflects the travel component value that is unrelated to departure time.[21] We calibrate this model to the situation of an airport like Los Angeles (LAX) in the third quarter of 2022. Table 1 summarizes the data, assumptions and calibrated parameters of the model.

Table 1
Data and assumptions. Airport LAX, 3^{rd}Q 2022.

Data:	
Monopoly and duopoly destinations	$M = 61$ and $N = 28$
Total destinations	$M + 2N = 117$
Total number of passengers, PAX million	60
Ratio of passengers on mono/duopoly destinations	0.40
Average fares, USD	247
Peak flight fare premium, %	30
Airport cost per passenger, USD	11
Airline share of variable cost, %	53
Power of passenger distributions (mono/duopoly)	$\alpha_M = 0.238$ and $\alpha_N = 0.586$
Assumptions:	
Peak capacity:	$K = 100$
Calibrated parameters	
s_0, s_1 and u, USD	230, 300 and 96
$\overline{z}_M$ and $\overline{z}_D$, PAX million	3.33 and 6.89
c, USD	120
$\widehat{\phi}$, USD	27.5
$\overline{\phi}$, USD	162.5

Using the DB1B database, with data for the third quarter of 2022,[22] we define a monopoly operator in a destination market as an airline with more than 90% of market share. Similarly, we define duopoly operators as the two airlines that together account for more than 90% of the market share (other configurations are ignored). In this way, we isolate $M = 61$ and $N = 26$ destinations with a monopoly and duopoly operator respectively. We aggregate all flights into a single pair of peak and off-peak periods and assume a total number of flights given by $M + 2N = 117$. We also assume inverse Pareto distributions for the size of the destination markets, $F(z) = \left(z/\overline{z}_M\right)^{\alpha_M}$ and $G(z) = \left(z/\overline{z}_D\right)^{\alpha_D}$ and estimate their power parameters α_M and α_N using OLS regression.[23] We calibrate $\overline{z}_M$ and $\overline{z}_D$ to match the total annual number of LAX passengers (60 million PAX) and the ratio of passengers in monopoly and duopoly destination markets computed from DBD1 (0.40).

We further calibrate s_0, s_1, and u to match the average direct-flight ticket price of USD 247 estimated in DB1B and to a peak-time premium of 0.30 reported in Lesgourgues and Malavolti (2023) (i.e., average on-peak price is equal to 1.3 times average off-peak prices). We set the airport variable cost k to 11 USD as equal to the LAX annual total operational expenses (USD 0.670 billion) divided by the number of its passengers. Assuming zero airport profit, the airport fee ϕ is also set to this value in the calibration. Finally, we calibrate the airline operating costs to 53% to match the average share of the flight crew, fuel, equipment, maintenance and user charges reported by the World Air Transport Statistics (2022). For the sake of the discussion, we set the peak capacity to $K = 100$ so that not all flights can be allocated to the peak period.

Fig. 4 shows the use of slot capacity in this setting when the passenger fee is set above the airport variable cost k. As shown in Proposition 1, allocative inefficiency emerges and some peak slots are left unused for $\phi \in \left(k, \widehat{\phi}\right)$, with $\widehat{\phi} = 27.5$ USD (see gray area). Above

[21] For this extension, the expressions of inverse travel demand p_i and p_{ij} simply include an additional term u while the airline's optimal number of seats q_{ij}, profits π_{ij}, and thresholds z_1, z_{01}, z_{11} and z^* require replacing ϕ with $\phi + c - u$. The airport profit and the welfare respectively include the variable costs k and $c + k$ times the number of passengers in each destination market. DUe to linear demand, the airport's optimal fees ϕ^* are shifted by a cost pass-through $(k - c + u)/2$.

[22] See Origin and Destination Survey Data, Bureau of Transportation Statistics, US Department of Transportation.

[23] These coefficients are highly significant and fit the destination travel demand with adj. R^2 equal to 0.90 and 0.87.

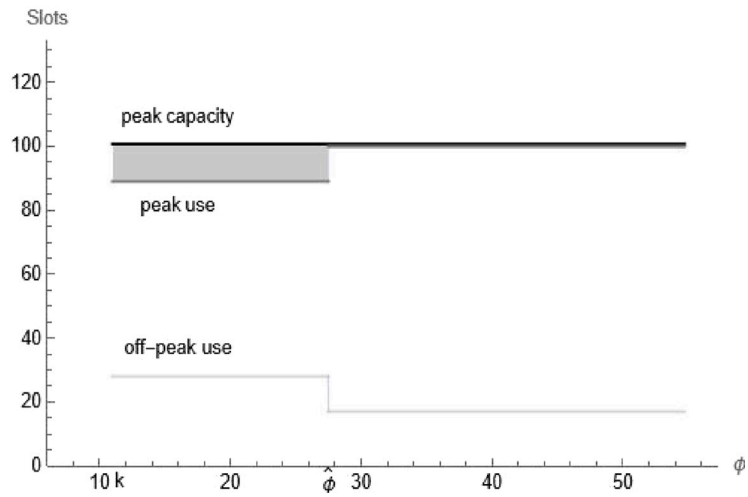

Fig. 4. Use of slot capacity.

this threshold, ticket prices rise and the number of passengers falls so that the airport does not find it profitable to separate duopoly flights in peak and off-peak times.

Fig. 5 examines the variation in welfare, airport's and airlines' profits as the per-passenger fee ϕ increases above k. It first shows the welfare value for which the slot allocation maximizes airport profit, given the airlines' and passengers' choices discussed above. It also shows the second-best welfare value for which the slot allocation maximizes welfare given airlines' and passengers' choices (see the calculation in Picard et al. (2019)). The figure shows that, at the initial fee $\phi = k$, welfare (USD 11.5 billion) is lower than the second best value (USD 14.1 billion), indicating the presence of an inefficient slot allocation as discussed in Proposition 6. An increase in ϕ then reduces both welfare measures. It can be seen from the figure that the second best welfare falls for any increase in fees, so the planner should impose a fee equal to the airport's variable cost if it is responsible for slot allocation. However, if the airport is responsible for the latter, welfare falls until the positive jump at $\phi = \hat{\phi}$ (27.5 USD), consistent with Proposition 6. The upward jump indicates a drastic welfare improvement due to the slot allocation, which is valued at USD 1.93 billion. This improvement is much larger than the USD 0.37 billion loss accrued to the rise of passenger fee from k to $\hat{\phi}$. It is also much larger than the airport's initial operating expenses of USD 0.67 billion used for the calibration. In contrast, airline profits do not change significantly at $\hat{\phi}$. Hence, in this example, airport liberalization increases welfare compared to a regulated airport that is constrained to set passenger fees equal to the airport's variable costs k but is free to allocate slots. In the presence of such a slot allocative inefficiency, the regulator would not reduce welfare by allowing the airport to raise its fee up to about 80 USD. However, in the case of full liberalization, the airport has an incentive to set a passenger fee of 142 USD, resulting in a significant welfare loss of USD 3.2 billion.

We now turn to verify the existence of an equilibrium with liberalized fees where ϕ should lie in the interval $\left[\hat{\phi}, \overline{\phi}\right)$. The left panel of Fig. 6 illustrates the optimal per-passenger fee levied by the airport for peak-time capacity, ranging from 20 to 117. It demonstrates that ϕ^* lies in the interval $\left[\hat{\phi}, \overline{\phi}\right)$, which is consistent with an efficient slot allocation. This exercise confirms the presence of an equilibrium where the airport fully exploits all available slots while controlling both the slot allocation and the passenger fees for monopoly and duopoly airlines. As shown earlier, the optimal passenger fee increases with the expansion of airport capacity (larger K), as the airport accommodates more flights during the peak period and airlines attract more passengers. Notably, in this calibrated example, the optimal fees are significantly higher than the per-passenger cost of airport services, indicating the exercise of a significant market power.

Finally, the right panel of Fig. 6 shows the corresponding optimal slot allocation and types of flights. In this panel, peak capacity K is displayed on the horizontal axis, while destinations/flights are counted on the vertical axis. The labels m_i and n_j denote the regions with flights to monopoly and duopoly destinations, with i indicating the departure period of the flight itself and j representing the competing flight's departure period ($i, j = 0$ for off-peak and 1 for peak). Peak flights are stacked from the bottom of the figure and off-peak flights are stacked from the top. Since each peak slot allows a departure to a peak destination, the 45° diagonal separates the sets of peak and off-peak flights: peak flights are below the diagonal and off-peak flights are above it. The top horizontal line represents all 117 destinations. The figure confirms that there are no unused slots. However, as the airport capacity decreases from its maximum level, the number of peak-to-peak duopoly flights is significantly reduced, eventually reaching zero ($n_{11} = 0$ at $K = 80$). For smaller capacities, the airport is so constrained that it allows only one duopoly flight at peak times, although it still avoids leaving any slots unused. This change in slot configuration explains the kink in the graph of the optimal fee in the left panel.

8. Different per passenger fees

This paper presents a stylized model of airport slot allocation using simplifying assumptions to maintain analytical clarity and focus. Specifically, we have assumed a uniform per-passenger fee for both peak and off-peak times, as is the common practice at most airports. However, many economists have argued in favor of differentiating such fees to reduce infrastructure congestion during peak hours. Consequently, we now briefly explore the implications of implementing per-passenger fees that vary between peak and off-peak times.

In this section, we study airline markets when per-passenger fees ϕ_i are higher at peak times, $\phi_1 > \phi_0$. Different per-passenger fees entail also different operating costs for airlines depending on the time of day they fly. We show that the airport's incentives to separate duopoly airlines in different time periods hold under certain conditions.

In monopoly destination markets and in time period i, each airline maximizes its profit $\pi_i(q, z) = \left[p_i(q, z) - \phi_i\right] q_i$ and chooses the seat capacity $q_i(z) = zq_i$ where $q_i \equiv \left(s_i - \phi_i\right) / \left(2s_i\right)$. The number of passengers remains larger in peak time under the condition

$$\frac{\phi_1}{s_1} \leq \frac{\phi_0}{s_0}. \quad (38)$$

That is, if passenger's fee relative to the willingness to pay is not larger in peak times. It can readily be shown that travel fares $p_i(z) =$

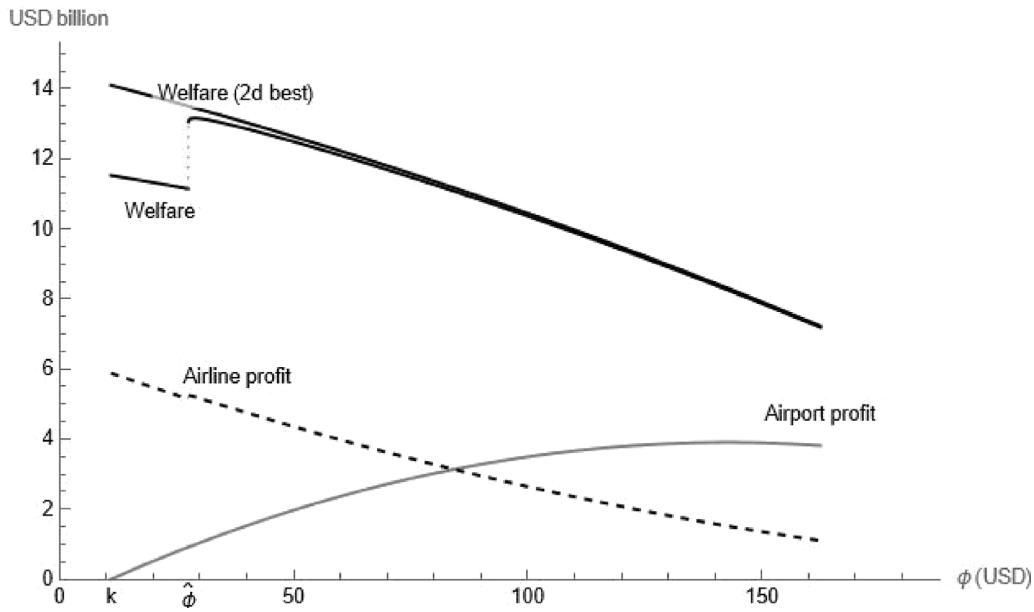

Fig. 5. Airport and airlines profits and welfare.

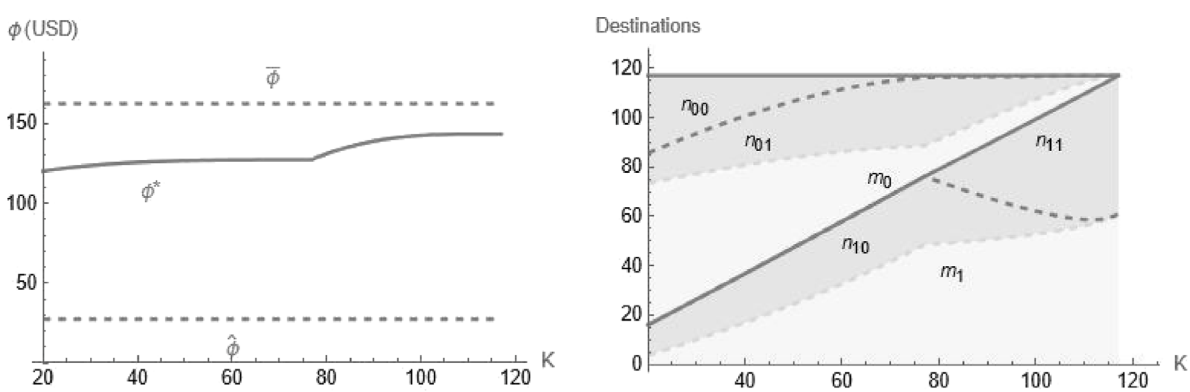

Fig. 6. Airport's profit maximizing fee and slot allocation as functions of airport peak capacity.

$p_i = (s_i + \phi_i)/2$ are always higher at peak time and that equilibrium monopoly profits $\pi_i(z) = z(s_i - \phi_i)^2/(4s_i)$ are positive if $\phi_i \leq s_i$, which we assume. It is natural to assume that condition (38) holds since otherwise, the airport has an incentive to move all monopoly airlines away from the peak, which is empirically inconsistent.

In duopoly destination markets, airlines operating in slots (i, j) independently choose their number of seats in order to maximize their profits. Similar to the text above, equilibrium seat capacities $q_{ij}(z)$ are given by $q_{ij}(z) = zq_{ij}$ where $q_{ii} = (s_i - \phi_i)/(3s_i)$ for flights on the same time period, $i = j$, and respectively,

$$q_{01} = \frac{2s_1(s_0 - \phi_0) - s_0(s_1 - \phi_1)}{s_0(4s_1 - s_0)} \text{ and } q_{10} = \frac{2(s_1 - \phi_1) - (s_0 - \phi_0)}{4s_1 - s_0},$$

for the off-peak and the on-peak flight. In the latter configuration, both profits are positive if and only if

$$\frac{1 - \phi_1/s_1}{1 - \phi_0/s_0} < 2.$$

The airport wants to separate duopoly airlines over peak and off-peak periods if and only if the property $q_{01} + q_{10} > 2q_{11}$ holds. This can be shown to be equivalent to

$$\frac{1 - \phi_1/s_1}{1 - \phi_0/s_0} > \frac{6s_1 - 3s_0}{5s_1 - 2s_0} \in (1, 2).$$

The LHS is larger than 1 under assumption (38). The airport separates duopoly airlines over different time periods if the passenger fee relative to the willingness to pay is sufficiently larger for peak periods than for off-peak times. This inequality collapses to $\phi < \hat{\phi}$ for a common fee $\phi \equiv \phi_i$ as in the main text.

9. Conclusions

In this paper, we explore the issue of allocative inefficiency in slot allocation at airports facing capacity constraints and oligopolistic airline structures. Slot allocation inefficiencies have been frequently highlighted in the airport management literature. As noted by Picard et al. (2019), slot coordination procedures that prioritize passenger traffic may inadvertently accentuate price discrimination between passengers and airlines during peak and off-peak periods. Our study examines the relationship between such inefficiencies and the liberalization of airport charges and revenues, and assesses their welfare implications. We emphasize that the liberalization of per-passenger fees can have a positive impact on the efficient use of airport infrastructure, leading to improved welfare through efficiency gains in slot allocation. However, the increase in per-passenger fees also reduces the net surplus of passengers and airline profits. Beyond a certain level, this increase reduces total welfare.

From a policy perspective, this paper provides valuable insights into the costs and benefits associated with the liberalization of airport charges. Our study suggests that deregulating these charges may either enhance or diminish welfare, depending on whether the improvements in slot allocation efficiency outweigh the negative impacts on passenger and airline economic surpluses. Specifically, the paper emphasizes that lower airport charges can reduce fares and stimulate travel demand, while they may also lead to inefficient slot utilization, potentially reducing overall welfare. One takeaway from this analysis is that "partial liberalization" could be socially desirable. In such a scenario, airports could set per-passenger charges up to a defined limit, thereby mitigating slot allocation inefficiencies. Our numerical example suggests that the social cost of slot allocation inefficiency can be significant and that the regulator may allow the airport to significantly increase passenger fees and reap a social welfare gain. These results provide valuable guidance for airport regulators in designing optimal policies.

For the sake of brevity, this analysis does not directly address travel delays caused by congestion and network effects. The first concern is somewhat mitigated in our analysis, focusing on level-2 airports where delay concerns are less pronounced. Unused slots could nevertheless generate a favorable external effect. The impact of delays on passenger satisfaction may indeed be captured in their preferences by an effect proportional to the share of unused slots that permits better management of movement uncertainties during peak times (e.g., weather, accidents, rescheduling). In this case, the slot allocation inefficiency discussed in this paper would be associated with a welfare improvement, while the liberalization and increase of airport charges and revenues would put additional strain on delays and welfare.

Finally, our analysis could be extended to include network effects (e.g., hubs). These effects provide benefits to passengers by improving connectivity between airports or airlines, and they can be incorporated as fixed effects in the passenger utility functions. A positive fixed effect for a well-connected airport would stimulate an increase in demand for travel to all its destinations and airlines, prompting the latter to adjust prices and aircraft capacities accordingly. Provided that it affects all travel preferences uniformly, this effect should not significantly alter airline competition or slot allocation inefficiency. Conversely, a positive fixed effect for a well-connected airline would channel increased demand towards the destinations served by that airline. Consequently, a slot allocation procedure designed to optimize passenger flow would also prioritize this airline for peak slots. The detailed outcome of this process, however, is left to future research.

CRediT authorship contribution statement

Pierre M. Picard: Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization, Writing – review & editing. **Alessandro Tampieri:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization, Writing – review & editing. **Xi Wan:** Writing – original draft, Investigation, Formal analysis, Conceptualization, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.tranpol.2024.12.015.

Data availability

No data was used for the research described in the article.

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