# On the effects of airport capacity expansion under responsive airlines and elastic passenger demand

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## Abstract

This paper investigates the effect of airport expansion on air traffic and its implications on airport congestion, airline competition and the social welfare, considering various airport administrative regimes (i.e., profit-maximization, social welfare-maximization, and budget-constrained social welfare-maximization), airline market structures (i.e., perfectly competitive, oligopoly, monopoly, leader-follower), and passenger demand patterns (i.e., regard airlines as perfect substitutes or imperfect substitutes). We develop an analytical tri-level model to examine the air traffic equilibrium in the airport-airline-passenger system, the effect of airport capacity expansion on the traffic equilibrium, and the decisions of different stakeholders. Specifically, we examine the airport's decisions on capacity investment and charge policy in the first level, airlines' decisions on flight volume and airfare in the second level, and the passenger choice equilibrium in the third level. The analysis in this paper suggests that (i) airport capacity expansion may induce the airline market to over schedule flights which leads to a more congested airport (i.e., capacity paradox); (ii) with a given airport charge, the capacity paradox is more likely to occur in an airline market with fewer competitive airlines; (iii) given the same airport capacity and traffic, the capacity paradox is more likely to occur when the airport operator's objective is social welfare-maximization (compared with profit-maximization and budget-constrained social welfare-maximization); (iv) airlines with market power will internalize a portion of airport congestion based on their market share, while a leader airline with the knowledge of the follower's response will scale up or down their airfare in order to maximize its profit; (v) under different market structures, increasing airport charge always reduces the aggregate traffic volume when the airport capacity is fixed.

*Keywords:* Airport expansion, Air traffic congestion, Airlines competition, Sequential game, Welfare effects

## 1. Introduction

In recent decades, with the increasing volumes of passengers and flights, air traffic congestion has become increasingly severe in aviation systems worldwide. In year 2019, about 46.4% of flights in Europe experienced departure delay, and 19% of flights in the United States experienced an arrival delay larger than 15 minutes.[1] The estimated economic impact induced by flight delays worldwide was about $60 billion a year (Gopalakrishnan & Balakrishnan, 2021). Many studies have proposed solutions to relieve congestion from the demand side through congestion pricing (e.g., Brueckner, 2002; Zhang & Zhang, 2006; Czerny & Zhang, 2011) and slot auction (e.g., Le et al., 2004; Fukui, 2010). These solutions can help relieve congestion, but only to a certain extent due to the capacity constraint of the supply side. An airport's capacity is primarily determined by its number of runways. It is difficult to schedule more flights than the maximum slots available beyond the designed runway capacity, owing to strict safety requirements and operation standards (De Neufville et al., 2013). In this context, many airports decide to expand their capacity to

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[1]These facts are based on data from the Eurocontrol website (https://www.eurocontrol.int/sites/default/files/2020-04/eurocontrol-coda-digest-annual-report-2019.pdf)

relieve congestion and meet the soaring demand in the future. Hong Kong International Airport (HKIA), for example, has its third runway under construction. The maximum capacity of the existing two-runway system in HKIA is about 420,000 flights a year. There will be a gap of about 182,000 flights if the capacity remains constrained by 2030.[2] However, airport expansion is also criticized for the huge labor and capital investment and long gestation period. Winston (1991) has commented that the high cost and long lead-times associated with expansion projects suggest that society will be faced with a difficult and expensive catch-up task if it commits itself to reducing air traffic congestion or boosting the regional economy by building the new runway. It is important and necessary to carefully examine the effects of airport expansion, considering multiple stakeholders such as the airport, airlines, and passengers.

Extensive studies have been carried out to examine the spillover impact of airport expansion on the regional economic boost in terms of the employment or productivity growth (e.g., Brueckner, 2003; Sellner & Nagl, 2010; Gibbons & Wu, 2017; Fu et al., 2021) and agglomeration effects (e.g., Graham, 2007; Graham & Van Dender, 2011). As Zhang & Graham (2020) reviewed, the potential stimulating effect of an expanded airport on the local economy is the major argument of proponents, and they concluded that both in developing and developed economies, the causality from air transport to economic growth exists. This conclusion is supported by a series of empirical studies. For example, Fu et al. (2021) investigated the impacts of airport activities using real data in New Zealand's airport system and suggested that aviation activities positively affect regional economies. Brueckner (2003) estimated the potential employment growth in the Chicago area to be above 5% (almost 200,000 jobs) for a 50% increase in air traffic, given the proposed doubling flight capacity.

However, little attention is paid to the impacts of airport expansion from the microeconomic perspective. There is a growing body of microeconomic analysis in the air transport literature, for instance, airport pricing (e.g., Zhang & Zhang, 1997; Fu et al., 2006; Oum & Fu, 2007; Zhang et al., 2010; Yang & Zhang, 2011; Czerny & Zhang, 2014; Yang & Fu, 2015; Wan et al., 2015; Kidokoro et al., 2016), airport-airline structure (e.g., Francis et al., 2004; Oum & Fu, 2008; Fu et al., 2011; Xiao et al., 2016), air-rail competition and cooperation (e.g., Yang & Zhang, 2012; Jiang & Zhang, 2014; Takebayashi, 2015, 2016; Xia & Zhang, 2016; Jiang et al., 2017; Wang et al., 2018; Xia et al., 2019; Takebayashi, 2021; Li et al., 2022) and so on. The airport expansion can have substantial impacts on both airlines and passengers, as a number of adjustments to the operation procedure of passenger and cargo services, air traffic management, aircraft handling, and so forth are expected to respond to the airport expansion, and passengers will respond to the aforementioned changes when making travel choices. Fageda & Fernández-Villadangos (2009) reviewed the relationship between airport capacity and airline competition. Their results suggested that the removal of airport capacity constraints does make airlines more competitive, but only at large airports that are not hubs of network carriers. Dray (2020) reviewed the actual expansion impacts on aircraft size, flight frequency, number of carriers and destinations with empirical data.

The effect of capacity expansion on congestion is less studied. Intuitively, airport capacity expansion relieves the capacity constraint to some extent and is expected to reduce air traffic congestion. Nevertheless, reality does not always run as expected. In road transport literature, researchers have identified different capacity paradoxes, in the sense that adding capacity to the road network or transit service network produces counter-productive results if the traffic inducing/diverting effect outweighs the direct benefits of capacity expansion (Duranton & Turner, 2011; Graham et al., 2014). According to Zhang et al. (2014, 2016), the effect of road expansion in a bi-modal system depends on not only the fare decision, but also how the transit operator changes the service frequency in response to the road expansion and how travelers choose their travel modes between car or transit. Operators with different economic objectives generally will react differently to road expansion, which can lead to diverse outcomes. Analogously, capacity expansion at a congested airport can have a substantial impact on the existing market conditions in the aviation system. The effect of airport expansion should be systemically examined given that we may have different market structures for airlines, different flight frequency and airfare decisions, and different passenger choice equilibrium (e.g., whether to choose the airport in concern to travel or not, and which airline).

The most relevant studies to this paper are the analytical studies on airport/airline capacity and pricing strategies. In Table 1, we summarize the problem setting and key issues of the relevant references and compare them with this paper. Brueckner (2002) was one of the earliest studies that analytically investigated the congestion internalization and congestion pricing in different airline markets. Following studies extended this research to different contexts, e.g.,

[2]These facts come from the Legislative Council of Hong Kong Special Administrative Region of the People's Republic of China (https://www.legco.gov.hk/yr10-11/chinese/panels/edev/papers/edev0610cb1-2364-1-c.pdf)

Brueckner & Verhoef (2010) investigated the regulator's different airport charge policies and the influences of the airline market on airport charge; Liu et al. (2022) investigated the airport pricing and regulation issues in the presence of passenger demand uncertainty. Apart from pricing choices, some studies also considered the airport capacity decision. In particular, Zhang & Zhang (2003) and Zhang & Zhang (2006) investigated the timing of airport expansion and the size of airport capacity investment in different airport regimes, respectively. Zhang & Zhang (2010) introduced the concession operation into the airport capacity choice. Xiao et al. (2013, 2016, 2017) analyzed the effects of demand uncertainty, airport-airline vertical arrangements, and airport reserved capacity on airport capacity choices, respectively. Zhang & Zhang (2003) did not explicitly model the airline's choices, and Zhang & Zhang (2006, 2010) considered that airlines compete in a Cournot market. Many studies mainly considered symmetric airline market. Lin (2019) investigated the pricing and capacity investment for a congested airport with an asymmetric airline market. However, the effects of airport expansion on different stakeholders in a tri-level airport-airline-passenger system have not been systematically analyzed and are not fully clear. This paper, based on the tri-level airport-airline-passenger system, examines the effects of airport expansion on congestion delay, airline competition, and the social welfare in various administrative regimes and market structures.

**Table 1** Summary of analytical studies on airport capacity and pricing choices

| Article | Decision makers | | | Air traffic congestion | Airport expansion | Airlines' market power | Asymmetric airlines | Key issues in this study |
|---|---|---|---|---|---|---|---|---|
| | Airport | Airline | Passenger | | | | | |
| Brueckner (2002) | | ✓ | ✓ | ✓ | | ✓ | | internalization & pricing |
| Zhang & Zhang (2003) | ✓ | ✓* | | ✓ | ✓ | | | airport charges; timing of expansion |
| Zhang & Zhang (2006) | ✓ | ✓ | ✓* | ✓ | ✓ | ✓ | | size of expansion |
| Zhang & Zhang (2010) | ✓ | ✓ | ✓* | ✓ | ✓ | ✓ | | concession operation |
| Brueckner & Verhoef (2010) | | ✓ | | ✓ | | ✓ | ✓ | airlines' influences on airport charges |
| Xiao et al. (2013) | ✓ | | | | ✓ | | | capacity choice; demand uncertainty |
| Xiao et al. (2016) | ✓ | ✓* | | | ✓ | ✓ | | airport-airline vertical arrangement |
| Xiao et al. (2017) | ✓ | ✓ | ✓* | | ✓ | ✓ | | reserved capacity; real options |
| Lin (2019) | ✓ | ✓ | ✓* | ✓ | ✓ | ✓ | ✓ | asymmetric airlines; discriminatory charge |
| Liu et al. (2022) | ✓ | ✓ | | | | ✓ | | price-cap regulations; demand uncertainty |
| This paper | ✓ | ✓ | ✓* | ✓ | ✓ | ✓ | ✓ | effect of expansion; sequential game |

Note: * indicates that the equilibrium at this particular level is modeled by the elastic demand function rather than explicitly specifying the choices facing the decision maker at this specific level.

This paper examines the effects of airport expansion in the airport-airline-passenger system and focuses on the following main questions: (i) how airlines will respond to the airport expansion in different market structures; (ii) under what conditions the capacity expansion will improve the system performance, and under what conditions the capacity paradox (a larger capacity leads to more severe congested delay) will occur; (iii) how airport expansion will

influence the passenger demand and social welfare. To this end, we build a tri-level airport-airline-passenger system and investigate the decisions and interactions among different stakeholders. In the third level, passengers choose which airline to travel with based on their travel costs. In the second level, airlines decide their flight traffic volume and airfare given passenger responses. In the first level, the airport makes its decisions on the airport capacity and airport charge given airline responses.

Several typical airport administrative regimes and airline market structures are considered. In the airport level, we consider an airport that may be operated in alternative administrative regimes (i.e., profit-maximization, social welfare-maximization, and budget-constrained social welfare-maximization), where the airport's charge per flight can be optimized in response to the airport capacity expansion. In the airline level, we consider four typical market structures for the airlines: competitive, monopoly, oligopolistic and leader-follower. We consider two passenger demand scenarios where airlines are perfect or imperfect substitutes for passengers. The airline market structures examined in each passenger demand scenario are summarized in Table 2.

**Table 2** Airline market structures and passenger demand scenarios considered in this paper

| Passenger demand scenario | Airline market structure |
|---|---|
| Perfect substitutes scenario | Perfectly competitive airlines |
| | Cournot airlines |
| | Monopoly airline |
| | A Stackelberg leader with a Cournot follower |
| Imperfect substitutes scenario | Duopoly airlines |
| | A Stackelberg leader with Cournot followers |

The major contributions of this paper are as follows: (i) It is the first to investigate the capacity paradox caused by airport expansion (i.e., the expansion may induce the airline market to over schedule flights and lead to a more congested airport), and establish analytical conditions for the capacity paradox to occur in different airport regimes and airline market structures; (ii) It is the first to systematically analyze the effects of airport capacity expansion on different stakeholders in the airport-airline-passenger system, e.g., the effects on passenger demand, airline profitability, airport congestion and the social welfare; (iii) It offers extensive analysis on different stakeholders' capacity and pricing strategies in various administrative regimes and market structures, especially in the asymmetric airline market which is less studied in the literature.

The rest of this paper is organized as follows. Section 2 presents the basic model formulations for cost, demand, and profit. In Section 3, we investigate the airlines' decisions and the resulting traffic equilibrium in response to airport expansion in different airline market structures. In Section 4, we investigate the airport's decisions with respect to capacity and pricing in three different airport administrative regimes, and examine how the decisions influence airlines' decisions and passenger choices. Section 5 presents numerical studies. Section 6 concludes the paper.

## 2. Model formulation

We consider a tri-level airport-airline-passenger system as shown in Figure 1, which follows that in Brueckner (2002), Zhang & Zhang (2003, 2006), and Brueckner & Van Dender (2008). In the first level, we consider a congested airport facing capacity and pricing (charge to airlines) decisions. The airport is served by $m$ airlines. In the second level, we examine decisions of airlines with respect to the flight volume and the airfare (charge to passengers) under different airline market structures. In the third level, passengers choose airlines based on their travel costs. Note that passenger choice is not explicitly specified but is reflected by the elastic demand function. To solve for the overall system equilibrium, the tri-level system is analyzed in the backward fashion, i.e., from the third level (passengers), to the second level (airlines), and to the first level (airport). Main notations are summarized in Table 3.

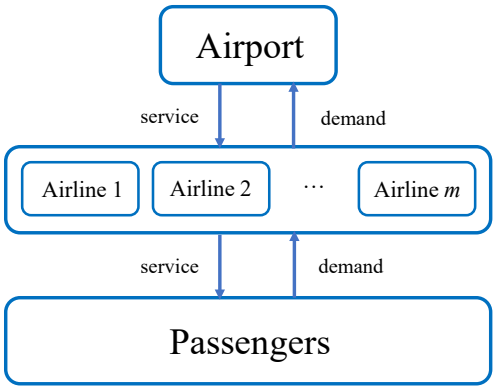



**Fig. 1.** Airport-airline-passenger system framework

**Table 3** List of main notations

| | | | |
|---|---|---|---|
| $t$ | average congestion delay | $k$ | airport capacity |
| $q_i$ | passenger demand for airline $i$ | $\rho$ | airport charge per passenger |
| $q$ | total passenger demand for all airlines ($q = \sum_i q_i$) | $r$ | airport concession profit per passenger |
| $p_i$ | full price of travel with airline $i$ | $c_k$ | airport capital investment cost per unit airport capacity |
| $\tau_i$ | airfare per passenger charged by airline $i$ | $c_q$ | airport's cost per passenger of handling flights |
| $m$ | number of airlines | $\pi_i$ | profit of airline $i$ |
| $c_f$ | airlines' fixed cost per passenger | $\Pi$ | profit of airport |
| $c_g$ | airlines' variable cost per passenger due to congestion delay | $SW$ | social welfare |

**(Air traffic congestion)** We model the average congestion delay per flight, which is a second-order differentiable function of flight traffic volume and capacity:

$$t = t(q, k), \tag{1}$$

where $t$ is the average congestion delay per flight, $k$ is the maximum runway and terminal capacity of handling flights and $q$ is the total flight traffic volume. Following Zhang & Zhang (2003, 2006, 2010), we consider that the congestion delay is increasing and convex with respect to the traffic volume $q$, and decreasing and convex with respect to capacity $k$, i.e., $t'_q = \partial t/\partial q > 0$, $t'_k = \partial t/\partial k < 0$, $t''_{qq} = \partial^2 t/\partial q^2 \geqslant 0$, $t''_{qk} = \partial^2 t/\partial q \partial k \leqslant 0$.

**(Passenger demand)** Passengers decide whether to travel through the airport in concern and which airline to take based on the full travel cost/price. The full price of traveling by airline $i$ is

$$p_i = \tau_i + t(q, k), i = 1...m. \tag{2}$$

The full price consists of two terms: the first term is the airfare of airline $i$, and the second term is the congestion cost. Passengers' value of time is normalized to one.

When airlines are perfect substitutes for passengers, the full price is identical among all airlines with non-zero traffic volume at the equilibrium, denoted by $p$. The total passenger demand is a function of the full price:

$$q = q(p), \tag{3}$$

where the demand function is assumed to be downward sloping (i.e., $q' < 0$).

When different airlines are imperfect substitutes for passengers, the demand for airline $i$ is a function of a series of full prices:

$$q_i = q_i(p_i, p_{-i}), \tag{4}$$

which depends on not only the price of this particular airline, but also those of all the alternatives, such that $\partial q_i/\partial p_i < 0$, $\partial q_i/\partial p_{-i} \geqslant 0$. If the substitutes are perfectly independent goods, $\partial q_i/\partial p_{-i} = 0$.

Eq. (1), Eq. (2) and the above demand functions Eqs. (3) or (4) together define the elastic demand equilibrium.

**(Effect of capacity expansion on congestion delay)** Depending on airlines' decisions, the equilibrium traffic volume $q$ varies with the airport capacity $k$. Thus, the effect of capacity expansion on congestion delay at the elastic demand equilibrium is given as follows:

$$\frac{\mathrm{d}t}{\mathrm{d}k} = t'_q \cdot \frac{\partial q}{\partial k} + t'_k. \tag{5}$$

According to Eq. (5), the overall effect of capacity expansion on congestion delay ($\mathrm{d}t/\mathrm{d}k$) equals the sum of two terms: (i) the congestion reduction due to the capacity expansion ($t'_k$), and (ii) the congestion increment caused by additional traffic volume attracted by the capacity expansion ($t'_q \cdot \partial q/\partial k$). If the congestion reduction can cover the congestion increment (i.e., $|t'_k| > |t'_q \cdot \partial q/\partial k|$), the expansion will relieve the congestion. Otherwise, the expansion will aggravate the congestion and lead to a "counterproductive" outcome, which is referred to as "capacity paradox" hereinafter in this paper.

**(Airline's profit)** The profit of an airline is equal to the ticket revenue from passengers minus the airport charges and the operation costs associated with flight volume and congestion delay. The profit of airline $i$ is as follows:

$$\pi_i = \tau_i q_i - \rho q_i - \Big[c_f + c_g t(q,k)\Big] q_i. \tag{6}$$

For each passenger, airline $i$ charges $\tau_i$ and pays for airport service $\rho$. The terms in the square brackets represent an airline's cost of operating flights, in which $c_f$ is airline's fixed cost per passenger, and $c_g t(q,k)$ represents the extra cost brought by air traffic congestion per passenger.[3]

**(Airport's profit)** The profit of the airport is equal to the charges/revenue collected from airlines for serving flights and passengers minus the capital investment cost related to airport capacity and the operation cost related to handling flights, i.e.,

$$\Pi = (\rho + r)q - (c_k k + c_q q). \tag{7}$$

The airport charges $\rho$ on each airline for each passenger served and derives a revenue of $r$ per passenger from the concession business. The total operation cost of the airport is $(c_k k + c_q q)$, where $c_k$ is the airport capital investment cost per unit airport capacity and $c_q$ is the operation cost per passenger of handling flights.

**(Social welfare)** The social welfare in the integrated airport-airline-passenger system is given as follows:

$$SW = \sum_i \left\{ \int_0^{q_i} p_i(\epsilon, q_{-i}) d\epsilon - p_i q_i + (\tau_i - \rho) q_i - [c_f + c_g t(q,k)] q_i \right\} + (\rho + r)q - (c_k k + c_q q), \tag{8}$$

where the social welfare is the sum of consumer surplus $\sum_i \{\int_0^{q_i} p_i(\epsilon, q_{-i}) d\epsilon - p_i q_i\}$, producer surplus that includes the sum of airlines' profit $\sum_i \{(\tau_i - \rho) q_i - [c_f + c_g t(q,k)] q_i\}$ and airport's profit $(\rho + r)q - (c_k k + c_q q)$.

## 3. Airline market equilibrium and responses to airport expansion

This section considers that airlines take the airport capacity and charge as given, and choose their traffic volumes and airfares to maximize their profits under different types of airline market structures. Passenger choice in the third level, reflected by the elastic demand function, is taken as an input in this level. In this section, we derive the pricing and output strategies of airlines, and investigate their responses to airport decisions. At this level, we focus on airline decisions while treating airport decisions as exogenously given (airport decisions will be further examined in Section 4).

[3] Here, we assume a constant marginal congestion cost brought by traffic volume, $c_g$. Future studies can consider to model $c_g$ as a general function of traffic volume, i.e., $c_g = c_g(q)$. This modification can capture the nonlinear effect of congestion delay on cost, but will somehow further complicate the mathematical expressions.

### 3.1. Perfect substitutes scenario

In this subsection, we consider that airlines are perfect substitutes for passengers, which means that all airlines provide homogeneous services. The full prices/costs for all airlines with non-zero traffic volume are identical at the equilibrium, which is denoted by $p$. Each airline produces an output (traffic volume in the unit of seat) of $q_i$ ($i = 1, ..., m$), and the total traffic volume of the airline market is $q = \sum_i q_i$. The full price of travel can be written as the inverse demand function $p = p(q)$ (demand is a function of cost/price). Since $p = \tau + t(q, k)$, the airfare can be written as $\tau = p(q) - t(q, k)$. Substituting the airfare into the airline's profit function Eq. (6), the profit of airline $i$ is as follows:

$$\pi_i = [p(q) - t(q, k) - \rho]\, q_i - \left[c_f + c_g t(q, k)\right] q_i. \tag{9}$$

Thus, the airline's profit function given by Eq. (9) has incorporated passenger responses. In what follows, we examine four airline market structures (in the perfect substitutes scenario), i.e., perfectly competitive airlines, Cournot airlines, monopoly airline, and a Stackelberg leader with a Cournot follower.

#### 3.1.1. Perfectly competitive airlines

In a perfectly competitive market, the profit margin of the airlines is zero ($\pi_i = 0$). We then can derive the airfare:

$$\tau = p(q) - t(q, k) = \underbrace{\rho}_{\substack{\text{airport charge per} \\ \text{passenger}}} + \underbrace{c_f + c_g t}_{\substack{\text{airline's operation} \\ \text{cost per passenger}}}. \tag{10}$$

Eq. (10) says that in a competitive airline market, the airfare equals the sum of airport charge and airline's operation cost per passenger. It is noteworthy that airport congestion externality is not internalized by the airline.

We now investigate how the equilibrium traffic volume $q$ responds to a marginal change in airport's decisions. Taking partial derivatives of $\pi_i = 0$ with respect to the airport capacity $k$ and airport charge $\rho$, respectively, we have

$$\frac{\partial q}{\partial k} = \frac{(1 + c_g) t'_k}{p' - (1 + c_g) t'_q} > 0, \tag{11a}$$

$$\frac{\partial q}{\partial \rho} = \frac{1}{p' - (1 + c_g) t'_q} < 0. \tag{11b}$$

Given the response functions, we now investigate how capacity expansion influences the airport congestion if the charge is fixed. Substituting Eq. (11a) into Eq. (5), we can derive the marginal effect of airport expansion on congestion delay.

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k p'}{p' - (1 + c_g) t'_q} < 0. \tag{12}$$

According to Eqs. (11a), (11b), and (12), we have Proposition 3.1.

**Proposition 3.1.** *In the perfect substitutes scenario with perfectly competitive airlines,*

*(i) if the airport charge $\rho$ is fixed, following a marginal increase of airport capacity $k$,*

*a. the traffic volume $q$ will increase,*

*b. the average congestion delay $t$ will decrease;*

*(ii) if the airport capacity $k$ is fixed, following a marginal increase of airport charge $\rho$, traffic volume $q$ will decrease.*

*Proof.* According to Eqs. (1) and (2), we have $t'_q > 0$, $t'_k < 0$, and $p' < 0$. Therefore, $(1+c_g)t'_k < 0$ and $[p' - (1+c_g)t'_q] < 0$. It is thus evident from Eqs. (11a), (11b), and (12) that $\partial q/\partial k > 0$, $\partial q/\partial \rho < 0$, and $\mathrm{d}t/\mathrm{d}k < 0$. This completes the proof. □

Proposition 3.1*(i)a* and *(ii)* state that airlines in the perfectly competitive market will schedule more flights when the airport decides to expand its capacity with a fixed charge, whereas fewer flights will be scheduled if the airport increases its charge with a fixed capacity. Proposition 3.1*(i)b* implies that the capacity paradox (expanding airport capacity leads to more congestion) will never occur when the airport charge is fixed. This is because that the traffic volume in the perfectly competitive market is at a relatively high level, and the airport expansion can only attract limited passengers. Thus, the congestion reduction due to the capacity expansion can cover the congestion increment caused by the additional traffic volume, and thus help to mitigate the congestion in the airport.

### *3.1.2. Cournot airlines*

We now consider that airlines have market power and compete in the Cournot fashion. Given airport capacity $k$ and charge $\rho$, each airline maximizes its own profit by choosing its optimal output level $q_i$. We can derive the first-order and second-order derivatives of the airline's profit function with respect to its own demand quantities $\partial\pi_i/\partial q_i$ and $\partial^2\pi_i/\partial q_i^2$ based on the airline profit formulation Eq. (9) treating the demand quantities of other airlines $q_{-i}$ as given.

The interior Cournot equilibrium is characterized by letting $\partial\pi_i/\partial q_i = 0$, and the second-order condition $\partial^2\pi_i/\partial q_i^2 < 0$ ensures the sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. Based on $\partial\pi_i/\partial q_i = 0$, we can derive the optimal quantity chosen by airline $i$

$$q_i = \frac{p - \rho - c_f - (1 + c_g)t}{(1 + c_g)t'_q - p'}, \tag{13}$$

and the airfare of airline $i$

$$\tau_i = \underbrace{\rho}_{\substack{\text{airport charge per}\\ \text{passenger}}} + \underbrace{c_f + c_g t}_{\substack{\text{airline's operation}\\ \text{cost per passenger}}} + \underbrace{(1 + c_g)t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per passenger}}} \cdot \underbrace{q_i}_{\substack{\text{airline } i\text{'s}\\ \text{traffic volume}}} + \underbrace{(-p'q_i)}_{\text{markup}} . \tag{14}$$

By comparing Eq. (10) and Eq. (14), it can be seen that the airfare of Cournot airlines has more terms than that of perfectly competitive airlines. In particular, Cournot airlines charge their passengers the airport charge $\rho$, the operation cost $(c_f + c_g t)$, the marginal congestion delay cost $(1+c_g)t'_q q_i$ (the Cournot airline internalizes the congestion externality related to its own traffic) and a markup of $(-p'q_i)$ that is proportional to its market share.

Following the classic models of quantity competition (e.g., Tirole, 1988), we further assume that airline outputs are strategic substitutes (Bulow et al., 1985), i.e., the marginal profit of one carrier will decline when other carriers' output rise $\partial^2\pi_i/\partial q_i\partial q_{-i} < 0$. One can verify that the "strategic substitutes" relationship and the second-order condition will hold under the assumption $p' < 0$ and $q_i p'' + p' < 0$.

We now investigate the marginal effects of the capacity expansion and airport charge increasing on the equilibrium traffic volume $q$. Taking partial derivatives of Eq. (13) with respect to airport capacity $k$ and airport charge $\rho$, we have

$$\frac{\partial q}{\partial k} = \frac{(1 + c_g)(qt''_{qk} + mt'_k)}{q\left[p'' - (1 + c_g)t''_{qq}\right] + (m + 1)\left[p' - (1 + c_g)t'_q\right]} > 0, \tag{15a}$$

$$\frac{\partial q}{\partial \rho} = \frac{m}{q\left[p'' - (1 + c_g)t''_{qq}\right] + (m + 1)\left[p' - (1 + c_g)t'_q\right]} < 0. \tag{15b}$$

The derivations for Eqs. (15a) and (15b) are provided in Appendix C.1. To obtain the effect of airport expansion on congestion delay under a given airport charge, we substitute Eq. (15a) into Eq. (5), which yields

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left\{q\left[p'' - (1 + c_g)t''_{qq}\right] + (m + 1)p' - (1 + c_g)t'_q + (1 + c_g)t'_q q \cdot t''_{qk}/t'_k\right\}}{q\left[p'' - (1 + c_g)t''_{qq}\right] + (m + 1)\left[p' - (1 + c_g)t'_q\right]}. \tag{16}$$

According to Eqs. (15a), (15b), and (16), we have Proposition 3.2.

**Proposition 3.2.** *In the perfect substitutes scenario with Cournot airlines,*

*(i) if the airport charge $\rho$ is fixed, following a marginal increase of airport capacity $k$,*

*a. the traffic volume $q$ will increase;*

*b. if* $\begin{cases} (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) > p'' + \dfrac{1}{q}\left[(m+1)p' - (1+c_g)t'_q\right] \\ (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) < p'' + \dfrac{1}{q}\left[(m+1)p' - (1+c_g)t'_q\right] \end{cases}$ *then* $\begin{matrix} \text{average congestion delay } t \text{ will decrease,} \\ \text{average congestion delay } t \text{ will increase;} \end{matrix}$

*(ii) if the airport capacity $k$ is fixed, following a marginal increase of airport charge $\rho$, traffic volume $q$ will decrease.*

*Proof.* The proof of Proposition 3.2 is provided in Appendix A.1. □

Proposition 3.2*(i)a* and *(ii)* imply that airlines in the Cournot market will schedule more flights following a marginal increase of airport capacity with a fixed airport charge and fewer flights following a marginal increase of airport charge with a fixed airport capacity, which is consistent with the finding of Zhang & Zhang (2006). Proposition 3.2*(i)b* also provides the condition for the occurrence of capacity paradox in the Cournot market, i.e., $(1+c_g)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < p'' + (1/q)[(m+1)p' - (1+c_g)t'_q]$. It is noted that when there are more airlines in the Cournot market (i.e., $m \to \infty$), Eq. (16) will approach Eq. (12) in the perfectly competitive market, where the capacity paradox will not occur. In addition, the shape of demand curve and congestion curve is critical to the occurrence of the capacity paradox. When the demand is more sensitive to the price (i.e., $|p''|$ and $|p'|$ are small) or when the airport congestion is more sensitive to flight traffic volume than capacity (i.e., $|t'_q|$ is relatively large and $|t'_k|$ is relatively small), the capacity paradox is more likely to occur.

In particular, we further assume the average congestion delay function $t = t(q,k)$ is homogeneous of degree zero with respect to airport capacity $k$ and traffic volume $q$, then $qt'_q + kt'_k = 0$. Thus, we have the following corollary.

**Corollary 1.** *In the perfect substitutes scenario with Cournot airlines, the capacity paradox will never occur if the congestion delay function $t = t(q,k)$ is homogeneous of degree zero in airport capacity $k$ and traffic volume $q$.*

*Proof.* Eq. (16) can be rewritten as

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left\{qp'' + (m+1)p' - (1+c_g)(qt''_{qq} + kt''_{qk} + t'_q)\right\}}{q\left[p'' - (1+c_g)t''_{qq}\right] + (m+1)\left[p' - (1+c_g)t'_q\right]} < 0. \tag{17}$$

Under the homogeneity of degree zero assumption, one can readily verify that the term $(qt''_{qq} + kt''_{qk} + t'_q)$ in the numerator is zero and thus we have $\mathrm{d}t/\mathrm{d}k < 0$. This implies that the capacity paradox will never occur. This completes the proof. □

When the average congestion delay function $t = t(q,k)$ is homogeneous of degree zero in $k$ and $q$, the marginal effects of traffic volume and capacity on congestion delay (i.e., $|t'_q|$ and $|t'_k|$) are at comparative levels. Thus, the capacity paradox will never occur. One can further verify that when the condition for the capacity paradox holds, the term $\mathrm{d}\,(t'_q/t'_k)/\mathrm{d}q$ will be positive and have a large value, which implies that a marginal increase of traffic volume at this point will significantly reduce airlines' and passengers' congestion cost. Thus, airlines have the incentive to over-schedule flights when airport capacity expands in such a market.

### *3.1.3. Monopoly airline*

In this subsection, we consider that the airport is dominated by a monopoly airline ($m = 1$) that maximizes its profit. We can derive the first-order derivative $\partial\pi/\partial q$ and second-order derivative $\partial^2\pi/\partial q^2$ from differentiating the airline profit $\pi$ with respect to the traffic volume $q$.

The interior monopoly solution is characterized by letting $\partial\pi/\partial q = 0$, and the second-order condition $\partial^2\pi/\partial q^2 < 0$ will ensure the sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. We then can

derive the quantity chosen by the monopoly airline

$$q = \frac{p - \rho - c_f - (1 + c_g)t}{(1 + c_g)t'_q - p'}, \tag{18}$$

and the airfare

$$\tau = \underbrace{\rho}_{\substack{\text{airport charge per} \\ \text{passenger}}} + \underbrace{c_f + c_g t}_{\substack{\text{airline's operation} \\ \text{cost per passenger}}} + \underbrace{(1 + c_g)t'_q}_{\substack{\text{marginal congestion} \\ \text{cost per passenger}}} \cdot \underbrace{q}_{\substack{\text{total traffic} \\ \text{volume}}} + \underbrace{(-p'q)}_{\text{markup}} . \tag{19}$$

Eq. (19) means that a monopoly airline will pass to its passengers the airport charge $\rho$, the operation cost $(c_f + c_g t)$, the marginal congestion delay cost $(1 + c_g)t'_q q$ (the monopoly airline fully internalizes the congestion externality of all traffic), and the monopoly markup of $(-p'q)$ (the monopoly markup is expected to be larger than the airline-specific markup in the Cournot model, where the market share affects the size of the markup).

We now turn to investigate how the equilibrium traffic volume responds to marginal changes of airport decisions. Taking partial derivatives of Eq. (18) with respect to airport capacity $k$ and airport charge $\rho$, we have

$$\frac{\partial q}{\partial k} = \frac{(1 + c_g)(t'_k + q t''_{qk})}{q\left[p'' - (1 + c_g)t''_{qq}\right] + 2\left[p' - (1 + c_g)t'_q\right]} > 0, \tag{20a}$$

$$\frac{\partial q}{\partial \rho} = \frac{1}{q\left[p'' - (1 + c_g)t''_{qq}\right] + 2\left[p' - (1 + c_g)t'_q\right]} < 0. \tag{20b}$$

The derivations for Eqs. (20a) and (20b) are similar to those of Eqs. (15a) and (15b) in Appendix C.1. The marginal effect of capacity expansion on the congestion delay with a fixed airport charge can be derived by substituting Eq. (20a) into Eq. (5), which yields

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left\{q\left[p'' - (1 + c_g)t''_{qq}\right] + 2p' - (1 + c_g)t'_q + (1 + c_g)t'_q q \cdot t''_{qk}/t'_k\right\}}{q\left[p'' - (1 + c_g)t''_{qq}\right] + 2\left[p' - (1 + c_g)t'_q\right]}. \tag{21}$$

One can verify that the monopoly model is equivalent to the Cournot model when the number of airlines reduces to one (i.e., $m = 1$). The results of the Cournot model in Proposition 3.2 hold for the monopoly airline by letting $m = 1$, and the condition for the capacity paradox to occur in a monopoly model is given by $(1 + c_g)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < p'' + (1/q)[2p' - (1 + c_g)t'_q]$. By comparing conditions (for the occurrence of the capacity paradox) in the Cournot model and monopoly model, one can see that given the same traffic volume $q$ and capacity $k$, the capacity paradox is more likely to occur in the airport with a monopoly airline. This is consistent with the results in the Cournot model that the capacity paradox is more likely to occur when there are fewer airlines in the market. One can also find a similar result to that of Corollary 1 for the monopoly market, i.e., the capacity paradox will never occur if the average congestion delay function is homogeneous of degree zero in airport capacity $k$ and traffic volume $q$.

### *3.1.4. A Stackelberg leader with a Cournot follower*

In this subsection, we consider that two different airlines compete in a leader-follower market ($m = 2$), i.e., the Stackelberg model. One airline leads and the other follows. The Stackelberg leader is indicated by subscript '$\ell$,' and the Cournot follower is indicated by subscript '$f$'. Different from previous subsections where airlines make their decisions simultaneously, this subsection considers that airlines move sequentially. In particular, Airline $\ell$ chooses $q_\ell$ first and is aware of how Airline $f$ would respond to its decision due to its dominant position in the market. Airline $f$ then chooses $q_f$ while taking $q_\ell$ as given.

In the sequential game, we first consider the follower's decision and derive its best response. Based on Airline $f$'s profit $\pi_f$, we can derive the first-order and second-order derivatives with respect to flight volume $q_f$, i.e., $\partial\pi_f/\partial q_f$ and $\partial^2\pi_f/\partial q_f^2$. An interior equilibrium is characterized by the first-order condition $\partial\pi_f/\partial q_f = 0$, and the second-

order condition $\partial^2\pi_f/\partial q_f^2 < 0$ ensures the sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. Based on the first-order condition $\partial\pi_f/\partial q_f = 0$, we can derive the optimal flight volume scheduled by Airline $f$:

$$q_f = \frac{p - \rho - c_f - (1 + c_g)t}{(1 + c_g)t'_q - p'}, \tag{22}$$

and the corresponding airfare chosen by Airline $f$:

$$\tau_f = \underbrace{\rho}_{\substack{\text{airport charge per}\\ \text{passenger}}} + \underbrace{c_f + c_g t}_{\substack{\text{airline's operation}\\ \text{cost per passenger}}} + \underbrace{(1 + c_g)t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per passenger}}} \cdot \underbrace{q_f}_{\substack{\text{Airline } f\text{'s}\\ \text{traffic volume}}} + \underbrace{(-p'q_f)}_{\text{markup}} . \tag{23}$$

Comparing Eq. (23) with Eq. (14), we find that the mathematical expression of the follower's optimal airfare contains similar terms to the Cournot model. This is because that as a follower, Airline $f$ is situated in a similar position to the Cournot airlines – they optimize the output with the leader/other airlines' decisions as given.

We further investigate the follower's response to a marginal change in $q_\ell$. Taking partial derivative of Eq. (22) with respect to $q_\ell$ yields

$$\frac{\partial q_f}{\partial q_\ell} = -\frac{\left[p'' - (1 + c_g)t''_{qq}\right]q_f + \left[p' - (1 + c_g)t'_q\right]}{\left[p'' - (1 + c_g)t''_{qq}\right]q_f + 2\left[p' - (1 + c_g)t'_q\right]}. \tag{24}$$

Given the second-order condition satisfying $\partial^2\pi_f/\partial q_f^2 < 0$, one can verify that the denominator in Eq. (24) is negative. Thus, the sign of Eq. (24) is up to its numerator. We can derive that $\partial q_f/\partial q_\ell \in (-1, -1/2)$ when $p'' < (1 + c_g)t''_{qq}$ (which will hold when the demand curve is concave or $p''$ is positive but small), which implies that the marginal increase of Airline $\ell$'s output will decrease Airline $f$'s output and increase the total output of airline market. This is also consistent with the "strategic substitutes" assumption (Bulow et al., 1985). In the following part of Section 3.1.4, to ease the presentation, we denote $\lambda \equiv \partial q_f/\partial q_\ell$, where $\lambda \in (-1, -1/2)$.

We now investigate the leader Airline $\ell$'s optimal decision. Airline $\ell$ chooses the traffic volume to maximize its profit when taking into account Airline $f$'s response. Similarly, we can derive the first-order condition $\partial\pi_\ell/\partial q_\ell = 0$ and the second-order condition $\partial^2\pi_\ell/\partial q_\ell^2 < 0$. Rewriting $\partial\pi_\ell/\partial q_\ell = 0$ gives to the optimal traffic volume $q_\ell$ and airfare $\tau_\ell$ chosen by Airline $\ell$

$$q_\ell = \frac{p - \rho - c_f - (1 + c_g)t}{(1 + \lambda)\left[(1 + c_g)t'_q - p'\right]}, \tag{25}$$

$$\tau_\ell = \underbrace{\rho}_{\substack{\text{airport charge per}\\ \text{passenger}}} + \underbrace{c_f + c_g t}_{\substack{\text{airline's operation}\\ \text{cost per passenger}}} + [\ \underbrace{(1 + c_g)t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per passenger}}} \cdot \underbrace{q_\ell}_{\substack{\text{Airline } \ell\text{'s}\\ \text{traffic volume}}} + \underbrace{(-p'q_\ell)}_{\text{markup}}\ ] \cdot \underbrace{(1 + \lambda)}_{\substack{\text{scale down}\\ \text{coefficient}}} . \tag{26}$$

The leader airline's airfare in Eq. (26) is different from while comparable to the follower's airfare and the airfare in the Cournot model. In particular, the first three terms that represent the airport charge and operation cost in Eq. (26) also appear in the follower's airfare. In the fourth term (related to the marginal congestion cost and markup), the term $q_\ell(1 + \lambda)$ reflects how the leader airline is able to incorporate the follower's response (i.e., $\lambda$) in its optimal decision. Moreover, when $\lambda = \partial q_f/\partial q_\ell \in (-1, -1/2)$, we have $0 < 1 + \lambda < 0.5$. This implies that by foreseeing the competition from the follower airline, the leader airline will scale down the terms related to the marginal congestion cost and markup in the airfare when compared with the counterpart in the Cournot model. Furthermore, by comparing the optimal airfare of the Airline $\ell$ and the Airline $f$ (i.e., Eqs. (26) and (23)), we have Remark 1.

**Remark 1.** *In the airline market with a Stackelberg leader and a Cournot follower, the leader airline will scale down the marginal congestion cost and markup in its airfare to the level that equals the counterpart of the follower's airfare.*

According to Eqs. (22) and (25), one can verify that the traffic volumes of Airline $f$ and Airline $\ell$ satisfy $q_f = q_\ell(1+\lambda)$, which brings the marginal congestion cost and markup in $\tau_f$ and $\tau_\ell$ to the same level. Remark 1 states that based on the knowledge of Airline $f$'s response, Airline $\ell$ will scale down its marginal congestion cost and markup to the level that equals to Airline $f$'s airfare, which ensures Airline $\ell$ a larger market share.

Comparing the output in the leader-follower market and the Cournot market with $m = 2$, one can derive that the leader-follower market produces more traffic volume than the Cournot market with $m = 2$, as $q_f = q_\ell(1+\lambda)$ and $\lambda < -1/2$. The detailed proof is provided in Appendix B.

We further investigate the airline market's response to airport decisions. Taking partial derivatives of Eq. (25) with respect to airport capacity $k$ and airport charge $\rho$, we have

$$\frac{\partial q}{\partial k} = \frac{(1+c_g)\left[(1+\lambda)q_\ell t''_{qk} + t'_k\right] - \left[p' - (1+c_g)t'_q\right]\frac{\mathrm{d}\lambda}{\mathrm{d}k}q_\ell}{\left[p'' - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + 2\left[p' - (1+c_g)t'_q\right]}, \tag{27a}$$

$$\frac{\partial q}{\partial \rho} = \frac{1 - \left[p' - (1+c_g)t'_q\right]\frac{\mathrm{d}\lambda}{\mathrm{d}\rho}q_\ell}{\left[p'' - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + 2\left[p' - (1+c_g)t'_q\right]} < 0. \tag{27b}$$

The derivations for Eqs. (27a) and (27b) are provided in Appendix C.2. Then, we investigate the effect of capacity expansion on the congestion delay. By substituting Eq. (27a) into Eq. (5), we have

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left\{(1+c_g)t'_q\left[1 + (1+\lambda)q_\ell \cdot t''_{qk}/t'_k\right] - \left[p' - (1+c_g)t'_q\right]\frac{\mathrm{d}\lambda}{\mathrm{d}k}q_\ell \cdot t'_q/t'_k\right\}}{\left[p'' - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + 2\left[p' - (1+c_g)t'_q\right]} + t'_k. \tag{28}$$

According to Eqs. (27a), (27b), and (28), we have Proposition 3.3.

**Proposition 3.3.** *In the perfect substitutes scenario with a Stackelberg leader and a Cournot follower,*

*(i) if the airport charge $\rho$ is fixed, following a marginal increase of airport capacity $k$,*

*a. if*
$$\begin{cases} \dfrac{\mathrm{d}\lambda}{\mathrm{d}k} < \dfrac{(1+c_g)\left[(1+\lambda)q_\ell t''_{qk} + t'_k\right]}{\left[p' - (1+c_g)t'_q\right]q_\ell} \\ \dfrac{\mathrm{d}\lambda}{\mathrm{d}k} > \dfrac{(1+c_g)\left[(1+\lambda)q_\ell t''_{qk} + t'_k\right]}{\left[p' - (1+c_g)t'_q\right]q_\ell} \end{cases} \text{ then } \begin{array}{l} \textit{traffic volume } q \textit{ will increase,} \\ \textit{traffic volume } q \textit{ will decrease;} \end{array}$$

*b. if*
$$\begin{cases} (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) > p'' + \dfrac{1}{(1+\lambda)q_\ell}\left\{2p' - (1+c_g)t'_q - \dfrac{t'_q}{t'_k}\left[p' - (1+c_g)t'_q\right]q_\ell\dfrac{\mathrm{d}\lambda}{\mathrm{d}k}\right\} \\ (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) < p'' + \dfrac{1}{(1+\lambda)q_\ell}\left\{2p' - (1+c_g)t'_q - \dfrac{t'_q}{t'_k}\left[p' - (1+c_g)t'_q\right]q_\ell\dfrac{\mathrm{d}\lambda}{\mathrm{d}k}\right\} \end{cases}$$
*then* $\begin{array}{l} \textit{average congestion delay } t \textit{ will decrease,} \\ \textit{average congestion delay } t \textit{ will increase;} \end{array}$

*(ii) if the airport capacity $k$ is fixed, following a marginal increase of airport charge $\rho$, traffic volume $q$ will decrease.*

*Proof.* The proof of Proposition 3.3 is provided in Appendix A.2. □

Proposition 3.3*(i)a* states that the leader-follower market with a Stackelberg leader and a Cournot follower will schedule fewer flights following the capacity expansion with a fixed airport charge when $\mathrm{d}\lambda/\mathrm{d}k > (1+c_g)[(1+\lambda)q_\ell t''_{qk} + t'_k]/[p' - (1+c_g)t'_q]$. This is because when $\mathrm{d}\lambda/\mathrm{d}k$ is positive and large, the Airline $f$ will be less sensitive to the Airline $\ell$'s decision on output, which implies that the competition from the follower will become fiercer. By foreseeing the competition, Airline $\ell$ will reduce its traffic volume. However, in the leader-follower market with $\lambda \in (-1, -1/2)$, the

decrease in $q_\ell$ will not increase $q_f$ in an equivalent amount; thus, the total traffic volume will decrease. According to Proposition 3.3*(i)b*, it is also noted that the capacity paradox will not occur when the total traffic volume decreases with the capacity expansion. Proposition 3.3*(i)b* also indicates that the capacity paradox is more likely to occur when $\mathrm{d}\lambda/\,\mathrm{d}k$ is negative (the follower is more sensitive to the leader's output when the airport is expanding). In this case, the leader will schedule more flights and capture most of the market share, and the market becomes closer to a monopoly market. Proposition 3.3*(ii)* implies that when the airport capacity is fixed, the marginal increase of airport charge will reduce traffic volume, which is consistent with findings in above scenarios.

### *3.2. Imperfect substitutes scenario*

In the real-world airline market, airlines often provide different services, which makes them imperfect substitutes for customers. For example, between a certain origin and destination, hub carriers often provide connecting services through their hub airports while direct carriers offer point-to-point services (Hansen, 1990). We examine two market settings where airlines are imperfect substitutes for customers, i.e., duopoly airlines and a Stackelberg leader with Cournot followers.

#### *3.2.1. Duopoly airlines*

In this subsection, we consider that two airlines serving the market (Airline 1 and Airline 2) are imperfect substitutes. Different from the perfect substitutes scenario, the demand for airline $i$ ($i = 1, 2$) depends on not only the price of this particular airline, but also the alternative, which can be modeled by a multivariable function $q_1 = q_1(p_1, p_2)$. The inverse functions characterize the corresponding full prices under given flow pattern, denoted by $p_i = p_i(q_i, q_{-i})$, where $p'_{i(i)} = \partial p_i/\partial q_i < 0$, $p'_{i(-i)} = \partial p_i/\partial q_{-i} > 0$ ($i, -i \in \{1, 2\}$ and $i \neq -i$). We consider that the full price traveling by airline $i$ is more sensitive to its own traffic volume (when compared with the other airline's traffic volume), i.e., $|p'_{i(i)}| > |p'_{i(-i)}|$. Note that the derivatives $p'_{i(i)}$ and $p'_{i(-i)}$ under the imperfect substitutes scenario are related to both $q_i$ and $q_{-i}$, which are different from those in the perfect substitutes scenario.

It is assumed that the two airlines make decisions simultaneously treating the other airline's output as given. They are represented as airline $i$ and airline $-i$, where $i, -i \in \{1, 2\}$ and $i \neq -i$. Based on the airline's profit formulation in Section 2, we can derive the first-order derivative $\partial\pi_i/\partial q_i$ and second-order derivative $\partial^2\pi_i/\partial q_i^2$ for airline $i$ treating the output of the other airline $q_{-i}$ as given. An interior optimum is defined by letting $\partial\pi_i/\partial q_i = 0$, and $\partial^2\pi_i/\partial q_i^2 < 0$ ensures the sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. We then can derive Airline $i$'s optimal traffic volume

$$q_i = \frac{p_i - (1 + c_g)t - \rho - c_f}{(1 + c_g)t'_q - p'_{i(i)}}, \tag{29}$$

and Airline $i$'s airfare

$$\tau_i = \underbrace{\rho}_{\substack{\text{airport charge per}\\ \text{passenger}}} + \underbrace{c_f + c_g t}_{\substack{\text{airline's operation}\\ \text{cost per passenger}}} + \underbrace{(1 + c_g)t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per passenger}}} \cdot \underbrace{q_i}_{\substack{\text{airline } i\text{'s}\\ \text{traffic volume}}} + \underbrace{[-p'_{i(i)}q_i]}_{\text{markup}}. \tag{30}$$

The airfare in Eq. (30) is similar to that in the Cournot model when the two airlines are perfect substitutes, which cover airport charge, airline operation cost, marginal congestion cost, and markup. Note that $p'_{i(i)}$ in the markup term depends on both airlines $i$'s own traffic volume $q_i$ and the substitute's traffic volume $q_{-i}$, which is different from the perfect substitutes scenario.

We also consider that airlines' outputs in the imperfect substitutes scenario are strategic substitutes (Bulow et al., 1985), i.e., $\partial^2\pi_i/\partial q_i\partial q_{-i} < 0$. We then investigate the airline market's response to the marginal change of airport decisions. Taking partial derivatives of Eq. (29) with respect to capacity $k$ and airport charge $\rho$, we have

$$\frac{\partial q}{\partial k} = \frac{(1 + c_g)(t''_{qk}q_2 + t'_k)(\pi''_{1(11)} - \pi''_{1(12)}) + (1 + c_g)(t''_{qk}q_1 + t'_k)(\pi''_{2(22)} - \pi''_{2(21)})}{\pi''_{1(11)}\pi''_{2(22)} - \pi''_{1(12)}\pi''_{2(21)}} > 0, \tag{31a}$$

$$\frac{\partial q}{\partial \rho} = \frac{(\pi''_{1(11)} - \pi''_{1(12)}) + (\pi''_{2(22)} - \pi''_{2(21)})}{\pi''_{1(11)}\pi''_{2(22)} - \pi''_{1(12)}\pi''_{2(21)}} < 0, \tag{31b}$$

where

$$\pi''_{1(11)} = \frac{\partial^2 \pi_1}{\partial q_1^2} = \left[p''_{1(11)} - (1+c_g)t''_{qq}\right] q_1 + 2\left[p'_{1(1)} - (1+c_g)t'_q\right] < 0;$$

$$\pi''_{2(22)} = \frac{\partial^2 \pi_2}{\partial q_2^2} = \left[p''_{2(22)} - (1+c_g)t''_{qq}\right] q_2 + 2\left[p'_{2(2)} - (1+c_g)t'_q\right] < 0;$$

$$\pi''_{1(12)} = \frac{\partial^2 \pi_1}{\partial q_1 \partial q_2} = \left[p''_{1(12)} - (1+c_g)t''_{qq}\right] q_1 + \left[p'_{1(2)} - (1+c_g)t'_q\right] < 0;$$

$$\pi''_{2(21)} = \frac{\partial^2 \pi_2}{\partial q_2 \partial q_1} = \left[p''_{2(21)} - (1+c_g)t''_{qq}\right] q_2 + \left[p'_{2(1)} - (1+c_g)t'_q\right] < 0.$$

The derivations for Eqs. (31a) and (31b) are similar to those for Eqs. (15a) and (15b) in Appendix C.1. According to the second-order condition and "strategic substitutes" assumption, we have $\pi''_{i(ii)} < 0$ and $\pi''_{i(i,-i)} < 0$, where $i, -i \in \{1, 2\}$ and $i \neq -i$. We further assume that the effect of airline $i$'s traffic volume $q_i$ on its own profit margin is larger than the alternative's traffic volume, i.e., $|\pi''_{i(ii)}| > |\pi''_{i(i,-i)}|$, which also ensures that the Hessian determinant $(\pi''_{1(11)}\pi''_{2(22)} - \pi''_{1(12)}\pi''_{2(21)})$ is positive. According to Eqs. (31a) and (31b), we have Proposition 3.4.

**Proposition 3.4.** *In the imperfect substitutes scenario with duopoly airlines,*

*(i) if the airport charge $\rho$ is fixed, following a marginal increase of airport capacity $k$, traffic volume $q$ will increase;*

*(ii) if the airport capacity $k$ is fixed, following a marginal increase of airport charge $\rho$, traffic volume $q$ will decrease.*

*Proof.* Denominators of Eqs. (31a) and (31b) are the same, and are positive according to $\pi''_{i(ii)} < 0$, $\pi''_{i(i,-i)} < 0$ and $|\pi''_{i(ii)}| > |\pi''_{i(i,-i)}|$ $(i = 1, 2, -i = 1, 2, i \neq -i)$. Given $t''_{qk} \leqslant 0$ and $t'_k < 0$, the numerator of Eq. (31a) is positive, while the numerator of Eq. (31b) is negative. Combining these conditions one can verify that $\partial q/\partial k$ is positive and $\partial q/\partial \rho$ is negative. This completes the proof. □

Proposition 3.4 indicates that the capacity expansion will encourage the airline market to schedule more flights with a fixed airport charge, and the increasing airport charge will reduce flight traffic volume with a fixed airport capacity. We then investigate the influence of airport expansion on congestion under a given airport charge. Substituting Eq. (31a) into Eq. (5) yields

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left\{(1+c_g)t'_q\left[(1+q_1 t''_{qk}/t'_k)(\pi''_{2(22)} - \pi''_{2(21)}) + (1+q_2 t''_{qk}/t'_k)(\pi''_{1(11)} - \pi''_{1(12)})\right] + \pi''_{1(11)}\pi''_{2(22)} - \pi''_{1(12)}\pi''_{2(21)}\right\}}{\pi''_{1(11)}\pi''_{2(22)} - \pi''_{1(12)}\pi''_{2(21)}}. \tag{32}$$

Eq. (32) implies that the effect of capacity expansion on congestion is related to the characteristics of demand curves $q_i = q_i(p_i, p_{-i})$ and congestion function $t = t(q, k)$. Since the complexity of Eq. (32), in the following analysis we consider that the demand functions take the linear form $p_i = p_0 - \alpha q_i + \beta q_{-i}$, where $i, -i \in \{1, 2\}$ and $\alpha > \beta > 0$. Thus, Eq. (32) can be rewritten as:

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left[(1+c_g)q(t'_q \cdot t''_{qk}/t'_k - t''_{qq}) - 2\alpha + \beta - (1+c_g)t'_q\right]}{-(1+c_g)t''_{qq}q + 2\left[-\alpha - (1+c_g)t'_q\right] + \left[\beta - (1+c_g)t'_q\right]}. \tag{33}$$

Similar result to that in Corollary 1 can be verified based on Eq. (33), i.e., the capacity paradox will never occur if the average congestion delay function is homogeneous of degree zero in airport capacity $k$ and traffic volume $q$. According to Eq. (33), we also have Remark 2.

**Remark 2.** *In the imperfect substitutes scenario with duopoly airlines and linear demand function, if the airport charge $\rho$ is fixed, and satisfies*

$$(1+c_g)\left(t''_{qq}-\frac{t'_q}{t'_k}t''_{qk}\right)<\frac{1}{q}\left[\beta-2\alpha+(1+c_g)t'_q\right],$$

*the capacity paradox will occur.*

We now compare the conditions for the occurrence of the capacity paradox when airlines are imperfect substitutes and perfect substitutes. For the occurrence of the capacity paradox in perfect substitutes scenario with two Cournot airlines ($m = 2$) and a linear demand function ($p = p_0 - \gamma q, \gamma > 0$), the condition of the capacity paradox can be written as follows: $(1+c_g)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < (1/q)[-3\gamma - (1+c_g)t'_q]$. By comparing the conditions in imperfect substitutes and perfect substitutes scenarios with two competing airlines, it can be seen that if airport capacity $k$ and total traffic volume $q$ are identical in the two markets, the capacity paradox is more likely to occur in the imperfect substitutes scenario given that $\beta - 2\alpha > -3\gamma$ (which will hold if the parameters satisfy $\gamma \approx \alpha > \beta > 0$). This is consistent with earlier results that the flatter the demand curve is, the more likely the capacity paradox would occur. Note that in the perfect substitutes scenario, the term $-3\gamma$ associated with the total traffic volume $q$ in the Cournot model is now replaced by the term $-2\alpha$ associated with the airline's own output $q_i$ plus the term $\beta$ associated with the substitute's output $q_{-i}$.

### *3.2.2. A Stackelberg leader with Cournot followers*

Now suppose that the airline market has one Stackelberg leader and $n$ Cournot followers (i.e., $m = n + 1$). The leader is aware of followers' responses to its decisions due to its dominant market position. Followers will take the leader's decision as given when they make their decisions. Denote the Stackelberg leader as Airline $\ell$, and Cournot followers as Airline $f_i, i = 1, \cdots n$. Passengers are indifferent between services provided by all Cournot followers, which implies that all followers in the market can be seen as a whole. The full prices of all followers are identical at the equilibrium, which is denoted by $p_f = p_f(q_\ell, q_f)$, where $q_f = \sum_{i=1}^{n} q_{fi}$. The full price of the leader Airline $\ell$ is given by function $p_\ell = p_\ell(q_\ell, q_f)$. In particular, the price of airline $i$ is more sensitive to its own traffic volume (when compared with other airline's traffic volume), i.e., $|p'_{i(i)}| > |p'_{i(-i)}|, i = \ell, f$.

Similar to Subsection 3.1.4, we first investigate Airline $f_i$'s decision. Based on Airline $f_i$'s profit $\pi_{fi}$, we can derive the first-order and second-order derivatives, i.e, $\partial\pi_{fi}/\partial q_{fi}$ and $\partial^2\pi_{fi}/\partial q_{fi}^2$. The interior equilibrium is characterized by letting $\partial\pi_{fi}/\partial q_{fi} = 0$, and the second-order condition $\partial^2\pi_{fi}/\partial q_{fi}^2 < 0$ will ensure the sufficiency of the first-order optimality condition and the uniqueness of the equilibrium. We then can derive Airline $f_i$'s choice of traffic volume and airfare as follows:

$$q_{fi} = \frac{p_f - \rho - c_f - (1+c_g)t}{(1+c_g)t'_q - p'_{f(f)}}, \tag{34}$$

$$\tau_{fi} = \underbrace{\rho}_{\substack{\text{airport charge per}\\ \text{passenger}}} + \underbrace{c_f + c_g t}_{\substack{\text{airline's operation}\\ \text{cost per passenger}}} + \underbrace{(1+c_g)t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per passenger}}} \cdot \underbrace{q_{fi}}_{\substack{\text{Airline } f_i\text{'s}\\ \text{traffic volume}}} + \underbrace{[-p'_{f(f)}q_{fi}]}_{\text{markup}}. \tag{35}$$

The airfare in Eq. (35) is similar to those in the Stackelberg leader-follower model in the perfect substitutes scenario, except that the markup term $p'_{f(f)}$ depends on both Airline $f_i$'s traffic volume and Airline $\ell$'s traffic volume.

We further investigate the follower airline's response to a marginal change of the leader airline's output $q_\ell$. Taking partial derivative of Eq. (34) with respect to $q_\ell$ yields

$$\frac{\partial q_f}{\partial q_\ell} = -\frac{\left[p''_{f(f\ell)} - (1+c_g)t''_{qq}\right]q_f + n\left[p'_{f(\ell)} - (1+c_g)t'_q\right]}{\left[p''_{f(ff)} - (1+c_g)t''_{qq}\right]q_f + (n+1)\left[p'_{f(f)} - (1+c_g)t'_q\right]}. \tag{36}$$

Apart from the change of demand function between perfect and imperfect substitutes scenario, one can verify that the follower's response in the Stackelberg leader-follower model in the perfect substitutes scenario (i.e., Eq. (24) in

Section 3.1.4) is similar to Eq. (36) with only one follower (i.e., $n = 1$). In this subsection, we further consider that the number of followers in the market is large enough (i.e., $n \to +\infty$), and thus Eq. (37) can be rewritten as

$$\frac{\partial q_f}{\partial q_\ell} = -\frac{(1+c_g)t'_q - p'_{f(\ell)}}{(1+c_g)t'_q - p'_{f(f)}}. \tag{37}$$

Given $p'_{f(f)} < p'_{f(\ell)}$, we have $\partial q_f/\partial q_\ell \in (-1, 0)$, which implies that a marginal increase of Airline $\ell$'s flight output will reduce Airline $f$'s output and increase the total output of the airline market. Again, we denote $\lambda \equiv \partial q_f/\partial q_\ell$, where $\lambda \in (-1, 0)$ and $1 + \lambda \in (0, 1)$. In addition, it is noted that if $p'_{f(f)} = p'_{f(\ell)}$, i.e., in the perfect substitutes scenario, the response rate will be a constant ($\lambda \to -1$). The total traffic volume in the market will be constant as the marginal increase in $q_\ell$ will yield an equivalent decrease in $q_f$. We also note that the response of follower to the leader's choice (i.e., $\lambda$) is expected to be more sensitive in the perfect substitutes scenario with one leader airline and one Cournot follower (where $\lambda \in (-1, -0.5)$) than in the imperfect substitutes scenario with one leader airline and a group of Cournot followers (where $\lambda \in (-1, 0)$).

We now investigate Airline $\ell$'s optimal decision. An interior equilibrium is characterized by $\partial\pi_\ell/\partial q_\ell = 0$, and $\partial^2\pi_\ell/\partial q_\ell^2 < 0$ ensures that the first-order optimality condition is sufficient and the equilibrium is unique. By letting $\partial\pi_\ell/\partial q_\ell = 0$, we derive the optimal flight traffic volume $q_\ell$ and airfare $\tau_\ell$ chosen by Airline $\ell$, i.e.,

$$q_\ell = \frac{p_\ell - \rho - c_f - (1+c_g)t}{\left[(1+c_g)t'_q - p'_{\ell(\ell)}\right] + \lambda\left[(1+c_g)t'_q - p'_{\ell(f)}\right]}, \tag{38}$$

$$\tau_\ell = \underbrace{\rho}_{\substack{\text{airport charge per}\\ \text{passenger}}} + \underbrace{c_f + c_g t}_{\substack{\text{airline's operation}\\ \text{cost per passenger}}} + \underbrace{(1+c_g)t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per passenger}}} \cdot \underbrace{q_\ell}_{\substack{\text{Airline } \ell\text{'s}\\ \text{traffic volume}}} \cdot \underbrace{(1+\lambda)}_{\substack{\text{scale down}\\ \text{coefficient}}} + \underbrace{\left[-\left(p'_{\ell(\ell)} + p'_{\ell(f)}\lambda\right)q_\ell\right]}_{\text{markup}}. \tag{39}$$

Airline $\ell$'s airfare in Eq. (39) consists of similar components as the airfares of Cournot airlines (in Eq. (14)) and monopoly airline (in Eq. (19)) in the perfect substitutes scenario, and the duopoly airlines (in Eq. (30)) in the imperfect substitutes scenario, i.e., airport charge, operation cost, marginal congestion cost, and markup term. Similar to the Stackelberg leader in the perfect substitutes scenario, in the airfare in Eq. (39), the first three terms (covering the airport charge and operation cost) are identical to those of the followers in Eq. (35). The fourth term (related to the marginal congestion cost) and the last term (the markup) reflect that the leader airline is able to incorporate the followers' response (i.e., $\lambda$) in its optimal decision. As shown above, $(1 + \lambda)$ ranges between 0 and 1, and thus the fourth term indicates that by foreseeing the competition from the follower airlines, the leader airline will scale down the term related to the marginal congestion cost in the airfare when compared with the airfare formula of the duopoly airlines. The last term, $[-(p'_{\ell(\ell)} + p'_{\ell(f)}\lambda)q_\ell]$ indicates that the leader airline will scale up the term related to the markup (a larger market power) when compared with the airfare formula of the duopoly airlines.

It is also noteworthy that a leader airline with a large number of Cournot followers (i.e., $m \to +\infty$) in the perfect substitutes scenario will scale down the marginal congestion cost and markup terms in the airfare to zero (just like a fully competitive market discussed earlier), which is different from a leader airline with Cournot followers in the imperfect substitutes scenario discussed here. This is because, in the imperfect substitutes scenario, the follower cannot fully cover the decrease of the leader's market share (i.e., $\lambda \in (-1, 0)$), thus the leader is able to earn more profit by increasing its airfare (when compared with a fully competitive market).

We then investigate the airline market's response to the marginal changes of airport decisions. Taking partial derivatives of Eq. (38) with respect to capacity $k$ and airport charge $\rho$, respectively, we have

$$\frac{\partial q}{\partial k} = \frac{(1+c_g)\left[t''_{qk}(1+\lambda)q_\ell + t'_k\right] - \left[p'_{\ell(f)} - (1+c_g)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}}{\left[\delta - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + \frac{2}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right] + \frac{2\lambda}{1+\lambda}\left[p'_{\ell(f)} - (1+c_g)t'_q\right]}, \tag{40a}$$

$$\frac{\partial q}{\partial \rho}=\frac{1-\left[p'_{\ell(f)}-(1+c_g)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}\rho}}{\left[\delta-(1+c_g)t''_{qq}\right](1+\lambda)q_\ell+\frac{2}{1+\lambda}\left[p'_{\ell(\ell)}-(1+c_g)t'_q\right]+\frac{2\lambda}{1+\lambda}\left[p'_{\ell(f)}-(1+c_g)t'_q\right]}<0, \tag{40b}$$

where $\delta=[p''_{\ell(\ell\ell)}+\lambda p''_{\ell(\ell f)}+\lambda p''_{\ell(f\ell)}+\lambda^2 p''_{\ell(ff)}]/(1+\lambda)^2$. The derivations for Eqs.(40a) and (40b) are provided in Appendix C.3. According to Eqs. (40a) and (40b), we have Proposition 3.5.

**Proposition 3.5.** *In the imperfect substitutes scenario with a Stackelberg leader and Cournot followers,*

*(i) if the airport charge $\rho$ is fixed, following a marginal increase of airport capacity $k$,*

$$\textit{if}\ \begin{cases}\dfrac{\mathrm{d}\lambda}{\mathrm{d}k}<\dfrac{(1+c_g)\left[(1+\lambda)q_\ell t''_{qk}+t'_k\right]}{\left[p'_{\ell(f)}-(1+c_g)t'_q\right]q_\ell}\\ \dfrac{\mathrm{d}\lambda}{\mathrm{d}k}>\dfrac{(1+c_g)\left[(1+\lambda)q_\ell t''_{qk}+t'_k\right]}{\left[p'_{\ell(f)}-(1+c_g)t'_q\right]q_\ell}\end{cases}\ \textit{then}\ \begin{array}{l}\textit{traffic volume } q \textit{ will increase,}\\ \textit{traffic volume } q \textit{ will decrease;}\end{array}$$

*(ii) if the airport capacity $k$ is fixed, following a marginal increase of airport charge $\rho$, traffic volume $q$ will decrease.*

*Proof.* The proof of Proposition 3.5 is provided in Appendix A.3. □

Proposition 3.5 indicates that the marginal increase in airport charge can reduce the total flight volume, while the capacity expansion may not increase the traffic volume. Same as in the perfect substitutes scenario in Section 3.1.4, Airline $\ell$ will reduce its traffic volume when the competition from the follower becomes fiercer after the airport expansion.

We also investigate how airport capacity decisions influence the airport congestion under a given airport charge. Substituting Eq. (40a) into Eq. (5) yields

$$\frac{\mathrm{d}t}{\mathrm{d}k}=\frac{t'_k\left\{(1+c_g)t'_q\left[1+(1+\lambda)q_\ell\cdot t''_{qk}/t'_k\right]-\left[p'_{\ell(f)}-(1+c_g)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}\cdot t'_q/t'_k\right\}}{\left[\delta-(1+c_g)t''_{qq}\right](1+\lambda)q_\ell+\frac{2}{1+\lambda}\left[p'_{\ell(\ell)}-(1+c_g)t'_q\right]+\frac{2\lambda}{1+\lambda}\left[p'_{\ell(f)}-(1+c_g)t'_q\right]}+t'_k. \tag{41}$$

Eq. (41) indicates that the effect of capacity expansion on congestion is related to the shape of the demand function and congestion function. However, it is not straightforward to identify the sign of $\mathrm{d}t/\mathrm{d}k$. In the analysis below, we further discuss the effects of capacity expansion based on a linear demand function $p_i=p_0-\alpha q_i+\beta q_{-i}$, where $i,-i\in\{\ell,f\}, i\neq -i$, and $\alpha>\beta>0$. Eq. (41) can be rewritten as follows:

$$\frac{\mathrm{d}t}{\mathrm{d}k}=\frac{t'_k\left\{(1+c_g)(1+\lambda)q_\ell(t''_{qk}\cdot t'_q/t'_k-t''_{qq})-\frac{2}{1+\lambda}\alpha+\frac{2\lambda}{1+\lambda}\beta-(1+c_g)t'_q-\left[\beta-(1+c_g)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}\cdot t'_q/t'_k\right\}}{-(1+c_g)t''_{qq}(1+\lambda)q_\ell+\frac{2}{1+\lambda}\left[-\alpha-(1+c_g)t'_q\right]+\frac{2\lambda}{1+\lambda}\left[\beta-(1+c_g)t'_q\right]}. \tag{42}$$

According to Eq. (42), we have Remark 3.

**Remark 3.** *In the imperfect substitutes scenario with a Stackelberg leader and Cournot followers, if the airport charge $\rho$ is fixed, and satisfies*

$$(1+c_g)\left(t''_{qq}-\frac{t'_q}{t'_k}t''_{qk}\right)<\frac{1}{(1+\lambda)q_\ell}\left\{-\frac{2\alpha}{(1+\lambda)}+\frac{2\lambda\beta}{(1+\lambda)}-(1+c_g)t'_q-\left[\beta-(1+c_g)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}\cdot\frac{t'_q}{t'_k}\right\},$$

*the capacity paradox will occur.*

By comparing the above condition with that under duopoly airlines (Remark 2), it can be seen that given the same airport capacity $k$ and traffic volume $q$, the capacity paradox will be more likely to occur in the leader-follower market (i.e., a more relaxed condition), when $\mathrm{d}\lambda/\mathrm{d}k$ is negative. This finding is consistent with that in the perfect substitutes scenario.

To summarize, this section delineates airline responses to airport decisions (airport capacity and airport charge) in different airline market structures and with different passenger demand specifications. Through analyses of the six scenarios, we find that, in general, the airline market will schedule fewer flights with a marginal increase in airport charge, and more flights with an increase in airport capacity (except in the leader-follower market). This section also identifies conditions for the capacity paradox (airport capacity expansion leads to a larger congestion delay) under a given airport charge. In particular, the capacity paradox is more likely to occur in the market with fewer competing airlines (e.g., the capacity paradox will not occur in the perfectly competitive market while it is more likely to occur in the monopoly market). Moreover, in the Stackelberg model, when the leader's market share increases with the capacity expansion, i.e., the leader captures most of the market share, the capacity paradox is also more likely to occur.

## 4. Impact of airport expansion under different airport administrative regimes and responsive airlines

Based on the airlines' responses established in Section 3, this section further examines how the airport should optimize its decisions to achieve its objective and also investigates the effects of airport expansion on different stakeholders in the airport-airline-passenger system. This section considers three airport administrative regimes: profit-maximization, social welfare-maximization, and budget-constrained social welfare-maximization. To avoid tedious repetition and economize on space, this section presents analytical examination in a particular airline market structure, i.e., the perfectly competitive market (using the results from Section 3.1.1). Other airline market structures are covered in the numerical studies in Section 5.

In each administrative regime, we firstly identify the optimality conditions for airport charge $\rho$ and airport capacity $k$. Then, we investigate the marginal effect of capacity increase, assuming that the airport charge can be flexibly adjusted according to the capacity. The conditions for capacity paradox are explored in two cases: 1) the benchmark capacity is arbitrary, and 2) the benchmark capacity is set at the optimal capacity level.

### *4.1. Profit-maximizing airport*

In this subsection, we consider a private airport that optimizes the airport charge and airport capacity to maximize the profit. We derive the first-order derivatives $\partial\Pi/\partial\rho$, $\partial\Pi/\partial k$ based on the airport profit formulation in Eq. (7). Letting $\partial\Pi/\partial\rho = 0$ and $\partial\Pi/\partial k = 0$ and combining with Eqs. (11a) and (11b), we can derive the optimality conditions for airport capacity and airport charge as follows

$$k^* = arg\{-q(1+c_g)t'_k - c_k = 0\}, \tag{43}$$

$$\rho^* = c_q - r - \frac{q}{\partial q/\partial\rho} = \underbrace{c_q}_{\substack{\text{flight handling cost}\\ \text{per passenger}}} + \underbrace{(1+c_g)t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per passenger}}} \cdot \underbrace{q}_{\substack{\text{total traffic}\\ \text{volume}}} + \underbrace{(-p'q)}_{\text{markup}} - \underbrace{r}_{\substack{\text{concession}\\ \text{profit per}\\ \text{passenger}}}. \tag{44}$$

Eq. (43) indicates that the optimal capacity of a profit-maximizing airport with perfectly competitive airlines is set at the level so that the marginal congestion cost reduction is equal to the marginal cost of capacity, which is consistent with the finding in Zhang & Zhang (2006). The optimal airport charge of a profit-maximizing airport with a perfectly competitive airline market shown in Eq. (44) says that the optimal airport charge consists of the flight handling cost $c_q$, the marginal congestion delay cost of all traffic in the market $(1+c_g)t'_q q$ and a markup term $(-p'q)$.

Considering that it is difficult for the airport to flexibly adjust its capacity in a short time or maintain the optimal capacity (Oum & Zhang, 1990), we do not restrict our analysis to the optimal capacity. We look into the suboptimal case where the airport optimizes the pricing decision under a given capacity. Thus, we investigate the marginal effect of airport capacity increase in two cases, i.e., 1) the benchmark capacity is arbitrary, and 2) the benchmark capacity is the optimal capacity level. For any given benchmark capacity level, the marginal effects of capacity increase on the

optimal airport charge $\rho^*$ and the flight volume $q$ can be derived as

$$\frac{\mathrm{d}\rho^*}{\mathrm{d}k} = -(1+c_g)t'_k + \frac{(1+c_g)(t''_{qk}q + t'_k)\left[p' - (1+c_g)t'_q\right]}{q\left[p'' - (1+c_g)t''_{qq}\right] + 2\left[p' - (1+c_g)t'_q\right]}, \tag{45}$$

$$\frac{\mathrm{d}q}{\mathrm{d}k} = \frac{(1+c_g)(t''_{qk}q + t'_k)}{q\left[p'' - (1+c_g)t''_{qq}\right] + 2\left[p' - (1+c_g)t'_q\right]} > 0. \tag{46}$$

The derivations for Eqs. (45) and (46) are provided in Appendix C.4. Substituting Eq. (46) into Eq. (5), we obtain the marginal effect of capacity expansion on congestion delay as follows

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left\{q\left[p'' - (1+c_g)t''_{qq}\right] + 2p' - (1+c_g)t'_q + (1+c_g)t'_q q \cdot t''_{qk}/t'_k\right\}}{q\left[p'' - (1+c_g)t''_{qq}\right] + 2\left[p' - (1+c_g)t'_q\right]}. \tag{47}$$

According to Eqs .(46) and (47), we have Proposition 4.1.

**Proposition 4.1.** *In a profit-maximizing airport with a perfectly competitive airline market, following a marginal increase of airport capacity (with reference to any capacity level),*

*(i) traffic volume q will increase;*

*(ii) if* $\begin{cases} (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) > p'' + \dfrac{1}{q}\left[2p' - (1+c_g)t'_q\right] \\ (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) < p'' + \dfrac{1}{q}\left[2p' - (1+c_g)t'_q\right] \end{cases}$ *then* $\begin{matrix} \textit{average congestion delay } t \textit{ will decrease,} \\ \textit{average congestion delay } t \textit{ will increase.} \end{matrix}$

*Proof.* The proof of Proposition 4.1 is provided in Appendix A.4. □

Combining Proposition 3.2*(i)* and Proposition 4.1, one can verify that the effects of airport capacity expansion in a profit-maximizing airport with a perfectly competitive airline market are similar to those with a monopoly airline for a given airport charge (Section 3.1.3). While no airport congestion externality is internalized by the airlines in a perfectly competitive market, a profit-maximizing airport has the market power and will pass the airport congestion externality to the airlines through the airport charge. We then investigate the reasons for the capacity paradox to occur. Comparing Eqs.(45) and (47), we have the following corollary.

**Corollary 2.** *In a profit-maximizing airport with a perfectly competitive airline market, the airport charge decreases with capacity expansion when the capacity paradox occurs.*

From Corollary 2, one can infer that the decreasing airport charge and the increasing airport capacity will encourage airlines to schedule more flights and eventually may incur the capacity paradox. We also note that the condition for the capacity paradox to occur can be rewritten as $q\cdot\partial(t'_q/t'_k)/\partial q > t'_k(qp'' + 2p') - (1+c_g)t'_q t'_k$, which implies that the marginal increase of traffic volume will lead to a larger value of $t'_q/t'_k$ and reduced airlines' and passengers' congestion costs. When the benefit is large enough (i.e., larger than $[t'_k(qp'' + 2p') - (1+c_g)t'_q t'_k]$), airlines will schedule more flights and incur the capacity paradox.

Based on the general capacity paradox condition in Proposition 4.1, in Corollary 3, we further derive the paradox condition for the special case where the benchmark capacity is the optimal level $k^*$. Substituting Eq. (43) into Eq. (47) yields

**Corollary 3.** *In a profit-maximizing airport with a perfectly competitive airline market (with reference to the optimal airport capacity level $k^*$),*

*if* $(1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) < p'' + \dfrac{2p'}{q} + \dfrac{t'_q}{t'_k}\dfrac{c_k}{q^2}$, *a marginal capacity expansion will lead to a larger congestion delay.*

According to Corollary 3, we find that the capacity paradox is likely to occur in the profit-maximizing airport when the airport is at its optimal capacity level $k^*$ and satisfies the condition $(1+c_g)(t''_{qq}-t''_{qk}t'_q/t'_k) < p''+2p'/q+(t'_q/t'_k)(c_k/q^2)$.

Now we examine the marginal effect of capacity expansion on the airport profit and social welfare, given any benchmark airport capacity and flexible airport charge adjustment. Differentiating Eq. (7) and Eq. (8) with respect to the capacity $k$, respectively, and combining with Eq. (44), we have

$$\frac{\mathrm{d}\Pi}{\mathrm{d}k} = -q(1+c_g)t'_k - c_k, \tag{48}$$

$$\frac{\mathrm{d}SW}{\mathrm{d}k} = -p'q\frac{\mathrm{d}q}{\mathrm{d}k} - q(1+c_g)t'_k - c_k. \tag{49}$$

According to Eqs. (48) and (49), we have Proposition 4.2.

**Proposition 4.2.** *In a profit-maximizing airport serving by perfectly competitive airlines, following a marginal increase of airport capacity (with reference to any capacity level),*

*(i) if* $\begin{cases} c_k < -q(1+c_g)t'_k \\ c_k > -q(1+c_g)t'_k \end{cases}$ *then* $\begin{array}{l} \textit{airport profit } \Pi \textit{ will increase,} \\ \textit{airport profit } \Pi \textit{ will decrease;} \end{array}$

*(ii) if* $\begin{cases} c_k < -q(1+c_g)t'_k - p'q\dfrac{\mathrm{d}q}{\mathrm{d}k} \\ c_k > -q(1+c_g)t'_k - p'q\dfrac{\mathrm{d}q}{\mathrm{d}k} \end{cases}$ *then* $\begin{array}{l} \textit{social welfare } SW \textit{ will increase,} \\ \textit{social welfare } SW \textit{ will decrease.} \end{array}$

*Proof.* The results in Proposition 4.2 are immediate from Eqs. (48) and (49). □

Proposition 4.2*(i)* states that airport profit may drop after the capacity expansion even if the airport can flexibly adjust the charge to maximize the profit. When the marginal benefit of additional capacity $[-q(1+c_g)t'_k]$ cannot cover the airport capital investment cost per unit capacity $c_k$, the airport profit will decrease. We have similar observations for the social welfare in Proposition 4.2*(ii)*, i.e., it can go down when the marginal cost is larger than the marginal benefit (associated with a marginal airport capacity expansion). Combining Eq. (43) and Proposition 4.2*(ii)*, we find that at the optimal capacity level $k^*$, the capacity expansion will increase the social welfare. In other words, the social welfare may increase even if the profit is decreasing. This is because, the increase of consumer surplus due to the increasing flight choice compensated the decrease of airport profit, leading to the improvement of the social welfare.

### *4.2. Social welfare-maximizing airport*

In this subsection, we consider a public airport that maximizes the social welfare. Based on the social welfare formulation given by Eq. (8), we can derive the first-order derivatives $\partial SW/\partial\rho$ and $\partial SW/\partial k$. We first investigate the optimal capacity and pricing decisions of the airport. Combine the first-order conditions $\partial SW/\partial\rho = 0$ and $\partial SW/\partial k = 0$, resulting in

$$k^* = arg\{-q(1+c_g)t'_k - c_k = 0\}, \tag{50}$$

$$\rho^* = \arg\{\tau - (1+c_g)t'_q q - (c_f + c_g t) + r - c_q = 0\}. \tag{51}$$

By comparing Eqs. (43) and (50), one can verify that the optimal airport capacity for a profit-maximizing airport and social welfare-maximizing airport have the same mathematical expression, i.e., the marginal congestion cost reduction equals the marginal cost of capacity. Eq. (51) states that under the optimal airport charge of a social welfare-maximizing airport, the airfare paid by a passenger will be equal to the marginal social cost. Substituting the

airfare formulation Eq. (10) into Eq. (51) yields

$$\rho^* = \underbrace{c_q}_{\substack{\text{flight handling cost}\\ \text{per passenger}}} + \underbrace{(1+c_g)t'_q}_{\substack{\text{marginal congestion}\\ \text{cost per passenger}}} \cdot \underbrace{q}_{\substack{\text{total traffic}\\ \text{volume}}} - \underbrace{r}_{\substack{\text{concession}\\ \text{profit per}\\ \text{passenger}}}. \tag{52}$$

The optimal airport charge shown in Eq. (52) is comparable to (while different from) that in profit-maximization regime in Eq. (44). The first, second and last terms of Eq. (52) associated with the flight handling cost per passenger $c_q$, congestion internalization $q(1+c_g)t'_q$ and concession profit per passenger $r$ are identical to those in Eq. (44), while social welfare-maximizing airport charge does not include the markup term. Thus, by comparing Eq. (52) and Eq. (44), it is noted that a social welfare-maximizing airport tends to charge less than a profit-maximizing airport.

We now investigate the effects of airport expansion starting from the sub-optimal case where only airport charge can be optimized, while the benchmark airport capacity is arbitrary. Differentiating Eq. (52) with respect to capacity $k$ yields

$$\frac{\mathrm{d}\rho^*}{\mathrm{d}k} = -(1+c_g)t'_k + \frac{(1+c_g)(t''_{qk}q + t'_k)[p' - (1+c_g)t'_q]}{p' - 2(1+c_g)t'_q - (1+c_g)t''_{qq}q}, \tag{53}$$

$$\frac{\mathrm{d}q}{\mathrm{d}k} = \frac{(1+c_g)(t''_{qk}q + t'_k)}{p' - 2(1+c_g)t'_q - (1+c_g)t''_{qq}q}. \tag{54}$$

The derivations for Eqs. (53) and (54) are similar to those of Eqs. (45) and (46), and thus omitted. Substituting Eq. (54) into Eq. (5), we obtain the marginal effect of airport expansion on congestion delay, i.e.,

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\left\{q(1+c_g)(t''_{qk}t'_q/t'_k - t''_{qq}) + [p' - (1+c_g)t'_q]\right\}}{p' - 2(1+c_g)t'_q - (1+c_g)t''_{qq}q}. \tag{55}$$

According to Eqs. (54) and (55), we have Proposition 4.3.

**Proposition 4.3.** *In a social welfare-maximizing airport serving by perfectly competitive airlines, following a marginal increase of airport capacity k (with reference to any capacity level),*

*(i) traffic volume q will increase;*

*(ii) if* $\begin{cases} (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) > \dfrac{1}{q}\left[p' - (1+c_g)t'_q\right] \\ (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) < \dfrac{1}{q}\left[p' - (1+c_g)t'_q\right] \end{cases}$ *then* $\begin{matrix} \text{average congestion delay } t \text{ will decrease,} \\ \text{average congestion delay } t \text{ will increase.} \end{matrix}$

*Proof.* The proof of Proposition 4.3 is provided in Appendix A.5. □

Proposition 4.3*(i)* states that in a social welfare-maximizing airport, competitive airlines will schedule significantly more flights following a marginal increase of airport capacity, leading to the increase of total flight volume. Proposition 4.3*(ii)* identifies the condition for the capacity paradox to occur, i.e., $(1+c_g)(t''_{qq} - t''_{qk}\cdot t'_q/t'_k) < (1/q)[p' - (1+c_g)t'_q]$. By comparing the capacity paradox conditions for the profit-maximization regime and social welfare-maximization regime, one can observe that given the same capacity $k$ and same traffic volume $q$, the capacity paradox is more likely to occur in a social welfare-maximization regime.

Based on the general capacity paradox condition in Proposition 4.3*(ii)*, in Corollary 4, we further derive the paradox condition for the special case where the benchmark capacity is the optimal level $k^*$, by substituting Eq. (50) into Eq. (55),

**Corollary 4.** *In a social welfare-maximizing airport with a perfectly competitive airline market (with reference to the optimal airport capacity level $k^*$),*

*if* $(1+c_g)\left(t''_{qq}-\frac{t'_q}{t'_k}t''_{qk}\right)<\frac{p'}{q}+\frac{t'_q}{t'_k}\frac{c_k}{q^2}$*, a marginal capacity expansion will lead to a larger congestion delay.*

We find that it is likely for the capacity paradox to occur in the social welfare-maximizing airport when the airport is at its optimal capacity level $k^*$ and satisfies the condition $q(1+c_g)(t''_{qq}-t''_{qk}t'_q/t'_k)<p'+(t'_q/t'_k)(c_k/q)$. In particular, we find that capacity expansion under these conditions will induce the airport to reduce the airport charge. Thus, the decreasing airport charge and increasing airport capacity will encourage airlines to schedule more flights and incur the capacity paradox.

We further investigate the influence of capacity expansion on the airport's profit and social welfare. Differentiating Eq. (7) and Eq. (8) with respect to capacity $k$, respectively, and combining with Eq. (52), we have

$$\frac{\mathrm{d}\Pi}{\mathrm{d}k}=p'q\frac{\mathrm{d}q}{\mathrm{d}k}-q(1+c_g)t'_k-c_k, \tag{56}$$

$$\frac{\mathrm{d}SW}{\mathrm{d}k}=-q(1+c_g)t'_k-c_k. \tag{57}$$

According to Eqs. (56) and (57), we have Proposition 4.4.

**Proposition 4.4.** *In a social welfare-maximizing airport with a perfectly competitive airline market, following a marginal increase of airport capacity (with reference to any capacity level),*

*(i) if* $\begin{cases} c_k<p'q\frac{\mathrm{d}q}{\mathrm{d}k}-q(1+c_g)t'_k \\ c_k>p'q\frac{\mathrm{d}q}{\mathrm{d}k}-q(1+c_g)t'_k \end{cases}$ *then* $\begin{array}{l} \text{airport profit } \Pi \text{ will increase,} \\ \text{airport profit } \Pi \text{ will decrease;} \end{array}$

*(ii) if* $\begin{cases} c_k<-q(1+c_g)t'_k \\ c_k>-q(1+c_g)t'_k \end{cases}$ *then* $\begin{array}{l} \text{social welfare } SW \text{ will increase,} \\ \text{social welfare } SW \text{ will decrease.} \end{array}$

*Proof.* Proposition 4.4 can be readily verified based on Eqs. (56) and (57). □

Proposition 4.4*(ii)* states that when the airport charge can be adjusted for achieving social welfare-maximization, increasing the capacity will enhance the social welfare given that the marginal airport capital investment cost $c_k$ is larger than the marginal benefit $[-q(1+c_g)t'_k]$. Combining Eq. (50) and Proposition 4.4*(i)*, we find that when the airport benchmark capacity is at the social welfare-maximizing level $k^*$, the airport capacity expansion will reduce the airport profit. By further comparing Proposition 4.2 and Proposition 4.4 (i.e., Eqs. (48) and (56), Eqs. (49) and (57)), one can observe that, with the same traffic volume $q$ and capacity $k$, additional capacity in a social welfare-maximization regime will bring less airport profit and social welfare than those in a profit-maximization regime.

### *4.3. Budget-constrained social welfare-maximizing airport*

We now consider a social welfare-maximizing airport subject to a profit constraint such that the airport profit should not be smaller than a certain value $h$. The social welfare and airport profit are given by Eqs .(7) and (8). Thus, the problem is formulated as

$$\begin{aligned} &\max_{\rho,k}\int_0^q p(\epsilon)d\epsilon-pq+(p-t-\rho)q-(c_f+c_gt)q+(\rho+r)q-(c_kk+c_qq) \\ &s.t.\quad (\rho+r)q-(c_kk+c_qq)\geqslant h \end{aligned} \tag{58}$$

Based on the problem formulation, we can form a Lagrangian function $\mathcal{L}=SW+\mu(\Pi-h)$ with $\mu$ being the Lagrangian multiplier, and derive the first-order derivatives, i.e., $\partial\mathcal{L}/\partial\rho$ and $\partial\mathcal{L}/\partial k$. Based on this, we firstly investigate the airport's optimal capacity and charge. An interior equilibrium is characterized by $\partial\mathcal{L}/\partial k=0$, $\partial\mathcal{L}/\partial\rho=0$, $\mu\geqslant 0$ and $\mu(\Pi-h)=0$. Based on the first-order conditions and Eqs. (11a) and (11b), we have:

$$k^*=arg\{-q(1+c_g)t'_k-c_k=0\}, \tag{59}$$

$$\rho^* = \frac{\mu}{1+\mu} \underbrace{\left[c_q + (1+c_g)t'_q q + (-p'q) - r\right]}_{\substack{\text{optimal airport charge in the} \\ \text{profit-maximization regime}}} + \frac{1}{1+\mu} \underbrace{\left[c_q + (1+c_g)t'_q q - r\right]}_{\substack{\text{optimal airport charge in the social} \\ \text{welfare-maximization regime}}} . \tag{60}$$

Eq. (59) specifies the optimal condition for the airport capacity in the budget-constrained social welfare-maximization regime, i.e., the marginal congestion cost reduction equals the marginal cost of capacity, which has the similar interpretation to those in the profit-maximization and social welfare-maximization regimes. The optimal condition for the airport charge in Eq. (60) is the weighted average of the optimal charges in the profit-maximization (given by Eq. (44)) and the social welfare-maximization regimes (given by Eq. (52)). The weight is determined by the multiplier $\mu$. We note that when $\mu = 0$, the budget constraint may not be binding, i.e., $\Pi \geqslant h$, and the airport charge will reduce to the same level as in a social welfare-maximizing regime; when $\mu$ is sufficiently large, the airport charge will raise to the same level as in a profit-maximizing regime. The optimal airport charge in Eq. (60) can be rearranged as $\rho^* = c_q + (1+c_g)t'_q q - r + \frac{\mu}{1+\mu}(-p'q)$.

We then investigate the marginal effects of capacity expansion on the airport charge and the airline market's output with reference to any given airport capacity level. Differentiating Eq. (60) with respect to capacity $k$ yields

$$\frac{\mathrm{d}\rho^*}{\mathrm{d}k} = -(1+c_g)t'_k + \frac{(1+c_g)(t''_{qk}q + t'_k)\left[p' - (1+c_g)t'_q\right]}{p' - (1+c_g)t''_{qq}q - 2(1+c_g)t'_q + \frac{\mu}{1+\mu}(p''q + p')}, \tag{61}$$

$$\frac{\mathrm{d}q}{\mathrm{d}k} = \frac{(1+c_g)(t''_{qk}q + t'_k)}{p' - (1+c_g)t''_{qq}q - 2(1+c_g)t'_q + \frac{\mu}{1+\mu}(p''q + p')}. \tag{62}$$

The derivations for Eqs. (61) and (62) are similar to those for Eqs. (45) and (46) provided in Appendix C.4. Then, we investigate the effect of airport expansion on the congestion delay. Substituting Eq. (62) into Eq. (5) yields

$$\frac{\mathrm{d}t}{\mathrm{d}k} = \frac{t'_k\{q(1+c_g)(t'_q t''_{qk}/t'_k - t''_{qq}) + \left[p' - (1+c_g)t'_q\right] + \frac{\mu}{1+\mu}(p''q + p')\}}{p' - (1+c_g)t''_{qq}q - 2(1+c_g)t'_q + \frac{\mu}{1+\mu}(p''q + p')}. \tag{63}$$

According to Eqs. (62) and (63), we have Proposition 4.5.

**Proposition 4.5.** *In a budget-constrained social welfare-maximizing airport with a perfectly competitive airline market, following a marginal increase of airport capacity (with reference to any capacity level),*

*(i) traffic volume $q$ will increase;*

*(ii) if*
$$\begin{cases} (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) > \dfrac{1}{q}\left[p' + \dfrac{\mu}{1+\mu}(p''q + p') - (1+c_g)t'_q\right] \\ (1+c_g)\left(t''_{qq} - \dfrac{t'_q}{t'_k}t''_{qk}\right) < \dfrac{1}{q}\left[p' + \dfrac{\mu}{1+\mu}(p''q + p') - (1+c_g)t'_q\right] \end{cases}$$
*then* *average congestion delay $t$ will decrease,* / *average congestion delay $t$ will increase.*

*Proof.* The proof of Proposition 4.5 is provided in Appendix A.6. □

Proposition 4.5*(i)* indicates that a perfectly competitive airline market in a budget-constrained social welfare-maximizing airport will schedule more flights following the marginal capacity expansion. Proposition 4.5*(ii)* identifies the condition for capacity paradox to occur, i.e., $q(1+c_g)\left(t''_{qq} - t''_{qk}\cdot t'_q/t'_k\right) < \left[p' - (1+c_g)t'_q\right] + \frac{\mu}{1+\mu}(p''q + p')$. It is noted that when $\mu$ is sufficiently large, the condition for the capacity paradox to occur in a budget-constrained social welfare-maximization regime will be relaxed to the same level as in the profit-maximization regime. Thus, one can

observe through these conditions in different airport regimes that, with the same capacity and traffic volume, the capacity paradox is more likely to occur in the social welfare-maximization regime and less likely to occur in the profit-maximization regime.

We further investigate the occurrence of the capacity paradox at the optimal airport capacity level $k^*$, and we have

**Corollary 5.** *In a budget-constrained social welfare-maximizing airport with a perfectly competitive airline market (with reference to the optimal airport capacity level $k^*$),*

*if* $(1+c_g)\left(t''_{qq}-\frac{t'_q}{t'_k}t''_{qk}\right)<\frac{p'}{q}+\frac{\mu}{1+\mu}\left(p''+\frac{p'}{q}\right)+\frac{t'_q}{t'_k}\frac{c_k}{q^2}$, *a marginal capacity expansion will lead to a larger congestion delay.*

We further investigate the influence of capacity expansion on the airport's profit and social welfare. Differentiating Eq. (7) and Eq. (8) with respect to capacity $k$, respectively, and combining with Eq. (60), we have

$$\frac{\mathrm{d}\Pi}{\mathrm{d}k}=\frac{1}{1+\mu}p'q\frac{\mathrm{d}q}{\mathrm{d}k}-q(1+c_g)t'_k-c_k, \tag{64}$$

$$\frac{\mathrm{d}SW}{\mathrm{d}k}=-\frac{\mu}{1+\mu}p'q\frac{\mathrm{d}q}{\mathrm{d}k}-q(1+c_g)t'_k-c_k. \tag{65}$$

According to Eqs. (64) and (65), we have Proposition 4.6.

**Proposition 4.6.** *In a budget-constrained social welfare-maximizing airport with a perfectly competitive airline market, following a marginal increase of airport capacity (with reference to any capacity level),*

*(i) if* $\begin{cases} c_k<\frac{1}{1+\mu}p'q\frac{\mathrm{d}q}{\mathrm{d}k}-q(1+c_g)t'_k \\ c_k>\frac{1}{1+\mu}p'q\frac{\mathrm{d}q}{\mathrm{d}k}-q(1+c_g)t'_k \end{cases}$ *then* $\begin{array}{l} \textit{airport profit } \Pi \textit{ will increase,} \\ \textit{airport profit } \Pi \textit{ will decrease;} \end{array}$

*(ii) if* $\begin{cases} c_k<-\frac{\mu}{1+\mu}p'q\frac{\mathrm{d}q}{\mathrm{d}k}-q(1+c_g)t'_k \\ c_k>-\frac{\mu}{1+\mu}p'q\frac{\mathrm{d}q}{\mathrm{d}k}-q(1+c_g)t'_k \end{cases}$ *then* $\begin{array}{l} \textit{social welfare } SW \textit{ will increase,} \\ \textit{social welfare } SW \textit{ will decrease.} \end{array}$

*Proof.* Proposition 4.6 can be readily verified based on Eqs. (64) and (65). □

Proposition 4.6 states that both airport profit and social welfare may decrease after a capacity expansion. Combining Eq. (59), Proposition 4.6*(i)* and *(ii)*, we find that the marginal capacity expansion will reduce airport profit but enhance the social welfare if the benchmark capacity is set at the optimal level for social welfare-maximization under budget constraint. By comparing the marginal effects of capacity expansion in the three regimes, i.e., profit-maximization (PM, Proposition 4.2), social welfare-maximization (SW, Proposition 4.4), and budget-constrained social welfare-maximization (BS, Proposition 4.6), we find that the marginal effect on airport profit is larger in PM regime, than BS and SW regimes (PM>BS>SW). Similar relationship is found for the marginal effect of airport expansion on social welfare, i.e., PM>BS>SW. Thus, *ceteris paribus*, airport expansion is more likely to benefit both the airport profitability and social welfare at a profit-maximizing airport.

## 5. Numerical studies

This section presents numerical studies to illustrate and explore the effects of airport expansion. The basic function forms and base-case parameter values are summarized in Table 4. If not further specified, the results are based on the base-case function and parameter settings.

Parameter values of airports and airlines are chosen with reference to data from Hong Kong International Airport (HKIA) and International Air Transport Association (IATA). As estimated in HKIA 2030 Outlook, the maximum capacity for the two-runway system in HKIA is about 440,000 flights a year. According to HKIA Annual Report 2018/19 (pre-pandemic), HKIA hosts about 75.1 million passengers and 429,000 flights in 2018/19 in total. Airport charges earned HKIA HK$5,255 million, and the concession business earned HK$7,145 million (including advertising revenue). The total cost was about HK$10,150 million (including amortization and depreciation). Thus, we can have a rough estimation of the value of airport concession profit per passenger $r$, airport capital investment cost per unit capacity $c_k$, and airport's cost per passenger of handling flights $c_q$. According to the 2018/19 Annual Report of major airlines operated in HKIA, we have a rough estimation of the airline's fixed cost per passenger $c_f$ and variable cost due to congestion $c_g$. In the budget-constrained social welfare-maximization regime, we set the budget constraint as airport profit being no smaller than HK$5 million. Other parameter values are assumed.

**Table 4** Basic functional forms and parameter values

| | Functional forms | Parameter values |
|---|---|---|
| Congestion time | $t(q,k) = w_1(q^{w_2}/k) + w_3 q$ | $w_1$ = 0.005<br>$w_2$ = 2<br>$w_2$ = 0.02 |
| Inverse demand function | $p(q) = c_{p0} - c_{p1}q$<br>$p_i(q_i) = c_{p0} - c_{pii}q_i + c_{pij}q_j$[1] | $c_{p0}$ = HK$3000<br>$c_{p1}$ = HK$0.01<br>$c_{pii}$ = HK$0.01<br>$c_{pij}$ = HK$0.005 |
| Airlines profit | $\pi_i = (\tau_i - \rho)q_i - [c_f + c_g t(q,k)]q_i$ | $c_f$ = HK$50<br>$c_g$ = HK$10 |
| Airport profit | $\Pi = (\rho + r)q - (c_k k + c_q q)$ | $r$ = HK$100<br>$c_k$ = HK$70<br>$c_q$ = HK$80 |

[1] This function is used when airlines are imperfect substitutes.

We first investigate the airline market's responses against the varying airport charge and capacity. Figure 2 shows the flight traffic volume and congestion delay of the airline market with different combinations of airport capacity and airport charge. We vary the capacity from 50,000 passengers per day to 250,000 passengers per day, and vary the airport charge from HK$ 40 per passenger to HK$ 120 per passenger. Generally, airport expansion will yield more traffic volume, and increasing the airport charge will reduce traffic volume. Moreover, the capacity paradox occurs in the monopoly market in the perfect substitutes scenario and duopoly airlines in the imperfect substitutes scenario. In addition, regarding traffic volume, perfectly competitive airlines yield the largest traffic volume, while monopoly provides the least traffic volume in the perfect substitutes scenario. The leader-follower market produces a higher traffic volume in both the perfect substitutes scenario and the imperfect substitutes scenario (in Figure 2(b), when compared with two airlines competing in a Cournot market ($m = 2$)).

We also take the airport's administrative regimes into consideration. Figures 3, 4, and 5 present the system responses to airport expansion in the profit-maximization, social welfare-maximization, and budget-constrained social welfare-maximization regimes, respectively. In each regime, the following airline market structures are examined, i.e., perfectly competitive airlines, Cournot airlines, monopoly airline, Stackelberg leader-a Cournot follower, duopoly airlines and Stackelberg leader-Cournot followers. It is noteworthy that Section 4 presents the analytical conditions for different airport regimes under the competitive airline market. In the numerical studies, we examine various combinations of airport administrative regimes and airline market structures.

Figures 3(a1) and 3(b1) present the traffic volumes of an airport in profit-maximization regime with different airline market structures. The perfectly competitive market produces the largest traffic volume, and the monopoly market produces the least traffic volume. It is also noted that the leader-follower market produces less output than the Cournot market with two airlines in the perfect substitutes scenario, but more output than duopoly airlines in the imperfect substitutes scenario. The main reason is that the airport can appropriately devise the airport charge to seek profit-maximization. In the welfare-maximization regime, Figures 4(a1) and 4(a3) show that the airline market structures have limited influence on the total traffic volume and the resultant social welfare. In some cases (monopoly

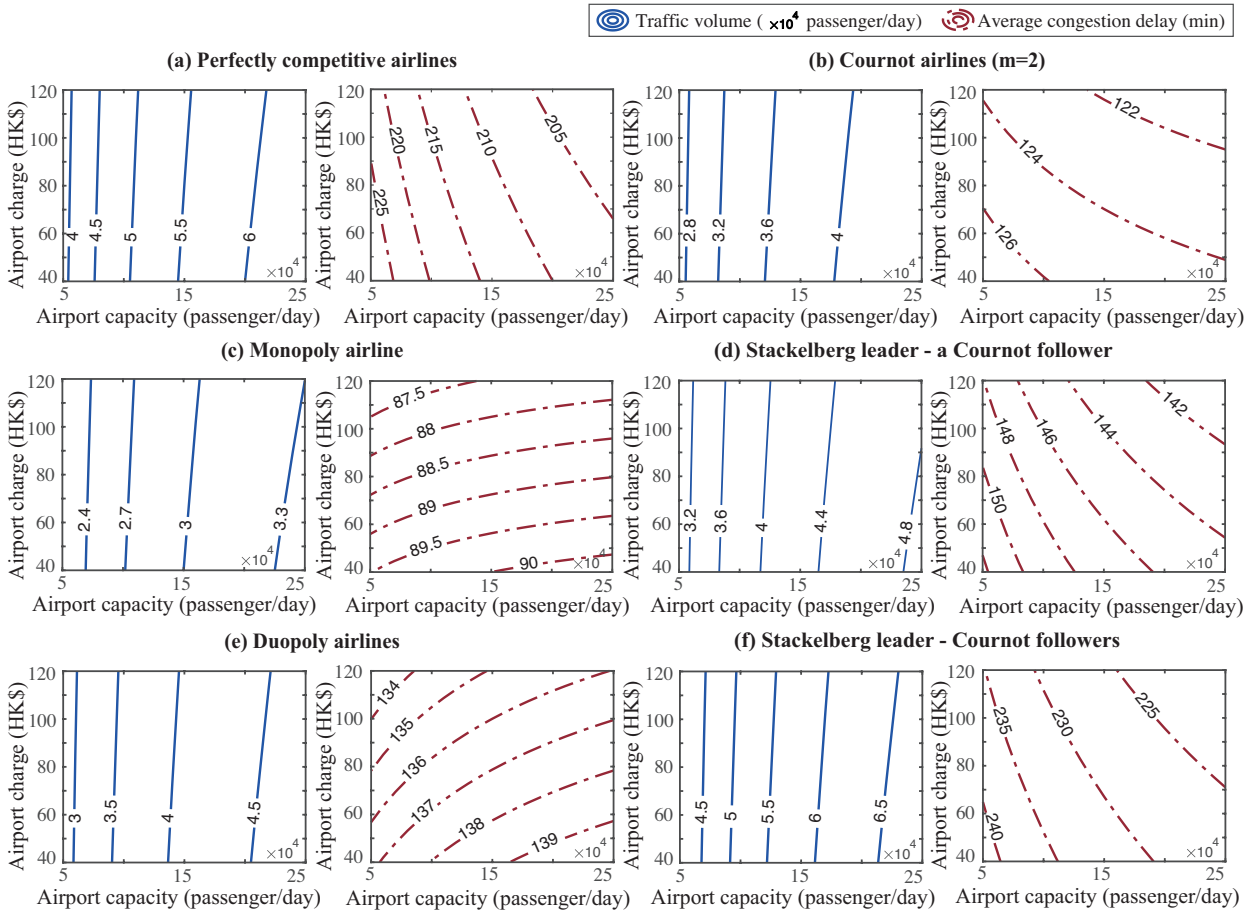



**Fig. 2.** Traffic volume and congestion delay under different airport charges and capacities

airline market), the airport charge is even negative, which means the airport will subsidize the airlines to encourage them to schedule more flights and improve the social welfare. However, in the imperfect substitutes scenario, Figures 4(b1) and (b3) show that the airline market structures will influence the total traffic volume and social welfare. Figures 5(a1) and 5(b1) show the traffic volumes of different airline market structures in a budget-constrained social welfare-maximizing airport. We find that when the airport profit is lower than the constraint, the airport will stop subsidizing the airline, which will reduce the total output and social welfare. However, if the budget constraint is not binding, it is identical to the social welfare-maximization regime, e.g., Figure 5(b) is the same as Figure 4(b).

Figures 3(a2), 3(b2), 4(a2), and 4(b2) show that the capacity paradox may occur in the profit-maximization regime and the social welfare-maximization regime, regardless of the airline market structure. However, in the budget-constrained social welfare-maximization regime, the congestion delay will drop in the base-case setting. Figure 5(a2) shows that the capacity paradox does not occur in the monopoly and Cournot markets when the airport budget constraint is binding.

The effects of airport expansion on social welfare and airport profit are shown in Figures 3(a3), 3(a4), 4(a3), 4(a4), 5(a3), and 5(a4). In particular, in Figure 3(a4), we find that the optimal capacity level for a profit-maximizing airport with perfectly competitive airlines is the largest. In Figure 4(a3), we find that the optimal level of the welfare-maximizing airport is the same for all airline market structures in the perfect substitutes scenario.

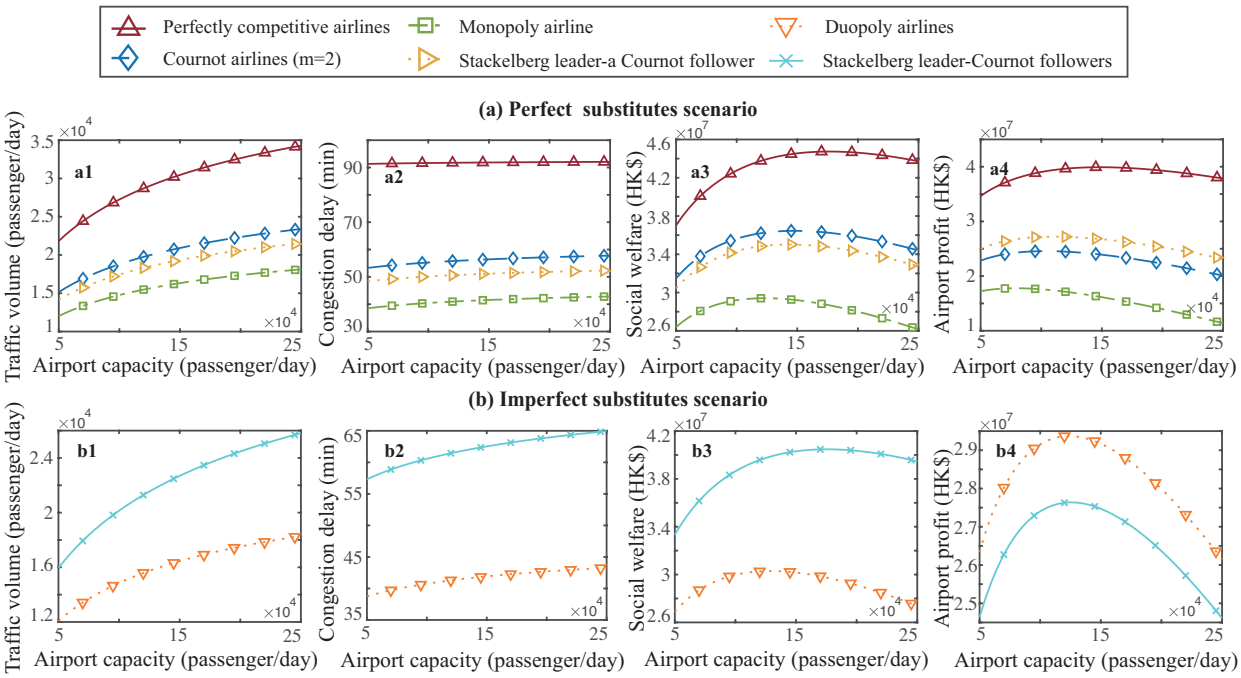



**Fig. 3.** Effects of the airport capacity expansion in the profit-maximizing administrative regime

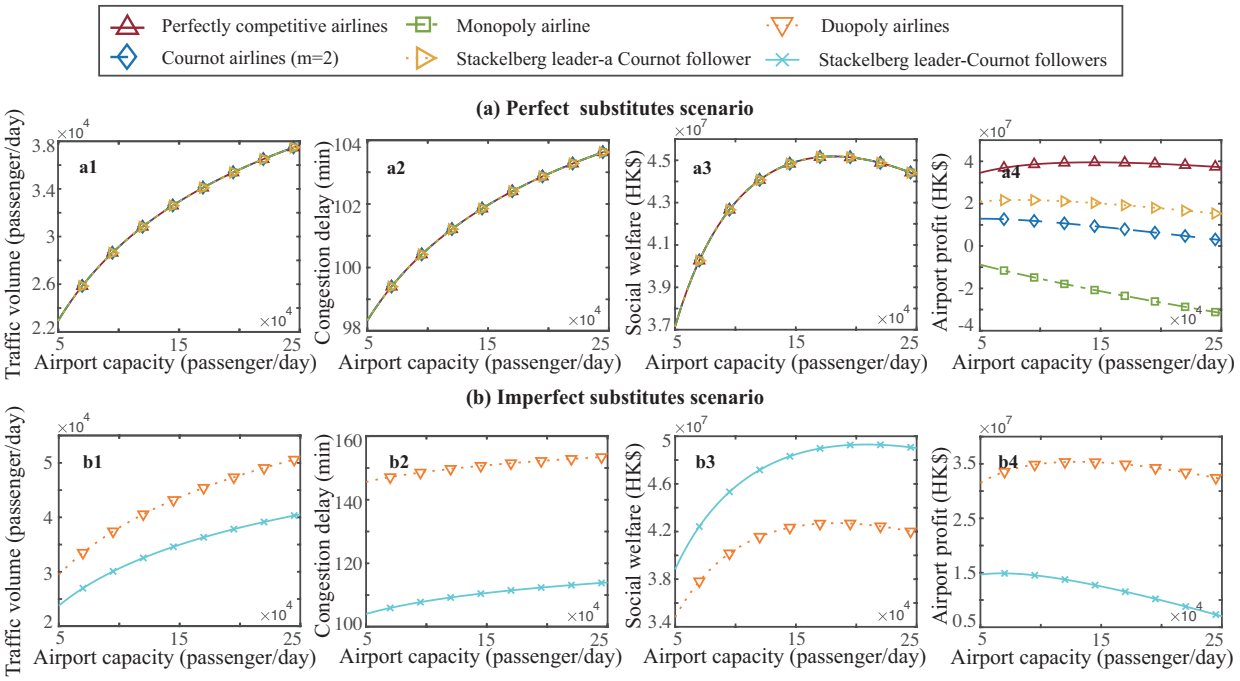



**Fig. 4.** Effects of the airport capacity expansion in the social welfare-maximizing administrative regime

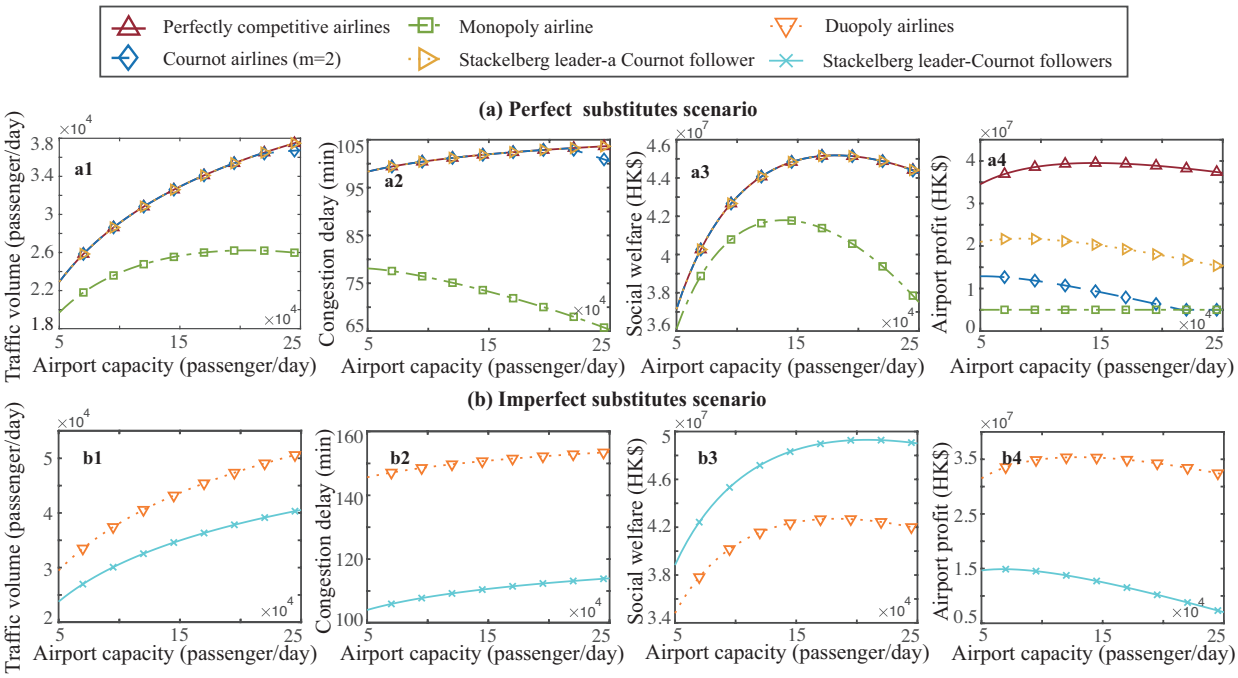



**Fig. 5.** Effects of the airport capacity expansion in the budget-constrained social welfare-maximizing administrative regime

## 6. Conclusion

In this paper, a tri-level game-theoretical model is developed to investigate the air traffic equilibrium in the airport-airlines-passenger system, the decisions of different stakeholders (airport, airlines, and passenger choices), and the effects of airport capacity expansion on the traffic equilibrium and a series of system efficiency metrics. We consider that, in the airport-airlines-passenger system, the airport might be operated in alternative administrative regimes, and the airline market might exhibit various structures. In this context, we examine different stakeholders' decisions and the implications on airport congestion, airline competition, and the social welfare.

The first part of the analysis examines the airline market's responses to varying airport decisions under given airport charge and capacity. We have the following findings. First, the capacity paradox is more likely to occur in the market with less competition. For example, in the symmetric airline market, the less airlines in the market (i.e., less $m$), the more likely for the capacity paradox to occur. Also, in the leader-follower market, when the leader captures most of the market share, the capacity paradox is more likely to occur. Second, the congestion internalization in different airline markets is different. A perfectly competitive airline market will not internalize any congestion, while in the Cournot market, airlines will internalize the congestion proportional to its market share. In a perfect substitutes airline market, the leader will scale down its airfare regarding airport congestion externality to the same level as the follower. However, in the imperfect substitutes scenario, the leader will charge more than the follower. Third, the shape of demand curve and congestion curve is critical to the occurrence of the capacity paradox. If the congestion delay is more sensitive to the traffic volume than the capacity (i.e., $|t'_q|$ is large while $|t'_k|$ is small) or traffic volume is very sensitive to price ($|p''|$ and $|p'|$ are small), the capacity paradox is more likely to occur. When the congestion delay function is homogeneous of degree zero in airport capacity and traffic volume, the capacity paradox will not occur in the perfect substitutes scenario. It is noteworthy that the capacity paradox does not imply that the economic contribution of the airport expansion has not increased. Although the airport can be more congested after the expansion, it does accommodate more demand, which means more economic interactions overall. Fourth, the increasing airport charge will reduce the traffic volume under a given capacity, regardless of the airline market structure. However, the capacity expansion under a given airport charge may not increase the traffic volume in the leader-follower market. When the competition from the follower becomes fiercer, the leader airline will reduce its traffic volume and eventually reduce the total output in the market.

The second part of the analysis considers the airport decisions in three airport administrative regimes and examines the impacts of the airport capacity expansion on system efficiency metrics considering airlines' responses. First, the occurrence of the capacity paradox is highly related to the airport's charge policy. We find that the capacity paradox is more likely to occur in the social welfare-maximization regime, as it charges less than in the profit-maximization regime, given the same capacity and traffic volume. It is also noted that the capacity paradox is more likely to occur when the airport charge decreases with capacity expansion. The decreasing airport charge and the increasing airport capacity may encourage airlines to schedule more flights and eventually incur the capacity paradox. We also find that the capacity paradox may occur even if the airport capacity is set to the optimal level. Second, the profit-maximization regime brings the lowest traffic volume, as it charges the highest airport charge. In a social welfare-maximization regime, the traffic volume is not influenced by the airline market structure in the perfect substitutes scenario. The airport will adjust its charge to ensure that the airfare paid by the passenger equals the marginal social cost, which means that the airport may offer a subsidy to the airlines when they need to receive more than the marginal social cost. However, if the social welfare-maximizing airport is subject to a budget constraint, it will stop paying more subsidies than the constraint allows.

This study can be extended in several ways. First, the model can be extended to incorporate the competition between full-service airlines (FSA) and low-cost carriers (LCC). Due to the differences in service type and business model, FSA and LCC may respond differently to the airport expansion. For example, when airlines make a trade-off between the marginal increase of flight traffic volume and the marginal increase of operation cost, FSA and LCC may have different strategies. To incorporate FSA vs. LCC competition, we should make several changes to the model formulation, e.g., we may consider a differentiated duopoly model, and the price sensitivity of LCC should be larger than that of FSA (Oum & Fu, 2007). This extension will derive more managerial insights into the real-world practice. Second, this study considers an identical aircraft size to maintain the analytical tractability. However, the aircraft size is an important decision for airlines, especially in congested airports. A larger aircraft can transport more passengers at once but may incur a larger flight cost (Richard, 2003). It is interesting to investigate airlines' integrated decisions on

aircraft size and pricing strategies facing congestion and capacity expansion. Third, this study considers the capacity investment and pricing decisions of an already congested airport, where capacity expansion is an exogenous decision. However, airport capacity expansion may also become an endogenous decision in response to changing demand. In future studies, we will consider the shifts of demand functions in different economic situations and investigate the responses of airline and airport capacity decisions to demand changes.

**Acknowledgement.** We are very grateful to the handling editor and three anonymous referees for their constructive comments that have led to a significant improvement of the paper. The work described in this paper was partially supported by the Research Grants Council of Hong Kong (No. 27202221), the National Natural Science Foundation of China (No. 72101222), and The Hong Kong Polytechnic University (P0039246, P0040900).

## Appendix A. Proofs of Propositions

### *Appendix A.1. Proof of Proposition 3.2*

Given $t'_k < 0$, $t''_{qk} \leqslant 0$, $c_g > 0$, $m > 0$, and $q \geqslant 0$, the numerator of Eq. (15a) is negative and the numerator of Eq. (15b) is positive. The denominators of Eqs. (15a) and (15b) are the same and are negative according to the "strategic substitutes" assumption, i.e., $\partial^2\pi_i/\partial q_i \partial q_{-i} < 0$. Therefore, we have $\partial q/\partial k > 0$ and $\partial q/\partial \rho < 0$, which implies that flight traffic volume will increase following the marginal airport capacity increase and decrease following the marginal increase of airport charge.

The denominator of Eq. (16) is the same as Eqs. (15a) and (15b), which is negative. Thus, the sign of $\mathrm{d}t/\,\mathrm{d}k$ is up to the numerator. One can verify that when the numerator is negative (i.e., $(1+c_g)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < p'' + (1/q)[(m+1)p' - (1+c_g)t'_q]$), we have $\mathrm{d}t/\,\mathrm{d}k > 0$, which implies that the capacity paradox occurs; when the numerator is positive (i.e., $(1+c_g)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) > p'' + (1/q)[(m+1)p' - (1+c_g)t'_q]$), we have $\mathrm{d}t/\,\mathrm{d}k < 0$. This completes the proof.

### *Appendix A.2. Proof of Proposition 3.3*

One can verify that the denominator of Eq. (27a) is negative according to the second-order condition $\partial^2\pi_f/\partial q_f^2 < 0$. Thus, the sign of $\partial q/\partial k$ is up to its numerator. One can verify that when the numerator of Eq. (27a) is negative (i.e., $\mathrm{d}\lambda/\,\mathrm{d}k < (1+c_g)[(1+\lambda)q_\ell t''_{qk} + t'_k]/[[p' - (1+c_g)t'_q]]$), we have $\partial q/\partial k > 0$, which implies that traffic volume will increase with the capacity expansion; when the numerator of Eq. (27a) is positive, we have $\partial q/\partial k < 0$, which implies that the traffic volume will decrease with the capacity expansion.

Eq. (27b) can be further simplified as follows:

$$\frac{\partial q}{\partial \rho} = \frac{1}{\left[p'' - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + \left[p' - (1+c_g)t'_q\right]\left[2 + q_\ell \frac{\mathrm{d}\lambda}{\mathrm{d}q_\ell} \cdot 1/(1+\lambda)\right]}. \tag{A.1}$$

The denominator of Eq. (A.1) is negative according to the second-order condition $\partial^2\pi_\ell/\partial q_\ell^2 < 0$. Thus, we have $\partial q/\partial \rho < 0$, i.e., the increasing airport charge will reduce traffic volume.

One can verify that the denominator of Eq. (28) is the same as Eqs. (27a) and (27b), which is also negative. Thus, the sign of $\mathrm{d}t/\,\mathrm{d}k$ is up to its numerator. One can verify that when the numerator is negative (i.e., $(1+c_g)(t''_{qq} - t''_{qk} \cdot t'_q/t'_k) < p'' + 1/(1+\lambda)q_\ell \cdot \{2p' - (1+c_g)t'_q - t'_q/t'_k \cdot [p' - (1+c_g)t'_q]q_\ell\, \mathrm{d}\lambda/\,\mathrm{d}k\}$), we have $\mathrm{d}t/\,\mathrm{d}k > 0$, which implies that the average congestion delay will increase with the marginal capacity expansion; when the numerator is positive (i.e., $(1+c_g)(t''_{qq} - t''_{qk} \cdot t'_q/t'_k) > p'' + 1/(1+\lambda)q_\ell \cdot \{2p' - (1+c_g)t'_q - t'_q/t'_k \cdot [p' - (1+c_g)t'_q]q_\ell\, \mathrm{d}\lambda/\,\mathrm{d}k\}$), we have $\mathrm{d}t/\,\mathrm{d}k < 0$. This completes the proof.

### *Appendix A.3. Proof of Proposition 3.5*

The denominator of Eq. (40a) is negative according to the second-order condition $\partial^2\pi_f/\partial q_f^2 < 0$. Thus, we have the sign of $\partial q/\partial k$ is up to its numerator. One can verify that when the numerator is negative (i.e.,$\mathrm{d}\lambda/\,\mathrm{d}k < (1+c_g)[(1+\lambda)q_\ell t''_{qk} + t'_k]/[p'_{\ell(f)} - (1+c_g)t'_q]$), we have $\partial q/\partial k > 0$, which implies that traffic volume will increase with the capacity expansion; when the numerator is positive (i.e.,$\mathrm{d}\lambda/\,\mathrm{d}k < (1+c_g)[(1+\lambda)q_\ell t''_{qk} + t'_k]/[p'_{\ell(f)} - (1+c_g)t'_q]$), we have $\partial q/\partial k < 0$, which implies that traffic volume will decrease with the capacity expansion.

Eq. (40b) can be further simplified as follows:

$$\frac{\partial q}{\partial \rho} = \frac{1}{\left[\delta - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + \frac{2}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right] + \frac{1}{1+\lambda}(2\lambda + q_\ell \frac{\mathrm{d}\lambda}{\mathrm{d}q_\ell})\left[p'_{\ell(f)} - (1+c_g)t'_q\right]}. \tag{A.2}$$

The denominator of Eq. (A.2) is negative according to the second-order condition $\partial^2\pi_\ell/\partial q_\ell^2 < 0$. Thus, we have $\partial q/\partial\rho < 0$, i.e., the marginal increase of airport charge will reduce the traffic volume. This completes the proof.

*Appendix A.4. Proof of Proposition 4.1*

One can readily verify that denominators of Eqs. (46) and 47 are the same, and are negative according to the second-order condition $\partial^2\Pi/\partial\rho^2 < 0$. Given $t'_k < 0$, $t''_{qk} \leqslant 0$, $c_g > 0$, and $q \geqslant 0$, we have the numerator of the Eq. (46) is negative, which implies that $\mathrm{d}q/\mathrm{d}k > 0$, and traffic volume will increase with the capacity expansion. The sign of $\mathrm{d}t/\mathrm{d}k$ is up to its numerator. One can verify that when the numerator is negative (i.e., $(1+c_g)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) < p'' + (1/q)[2p' - (1+c_g)t'_q]$), we have $\mathrm{d}t/\mathrm{d}k > 0$, which implies that the average congestion delay will increase with the marginal capacity expansion; when the numerator is positive (i.e., $(1+c_g)(t''_{qq} - t'_q/t'_k \cdot t''_{qk}) > p'' + (1/q)[2p' - (1+c_g)t'_q]$), we have $\mathrm{d}t/\mathrm{d}k < 0$.

*Appendix A.5. Proof of Proposition 4.3*

Given $p' < 0$, $t'_q > 0$, $t'_k < 0$, $t''_{qk} \leqslant 0$, $t''_{qq} \geqslant 0$, $c_g > 0$, and $q \geqslant 0$, both the numerator and denominator of Eq. (54) are negative. Therefore, we have $\partial q/\partial k > 0$, which implies that flight traffic volume will increase following the marginal capacity increase. The denominator of Eq. (55) is the same as Eq. (54), which is negative. Thus, the sign of $\mathrm{d}t/\mathrm{d}k$ is up to the numerator. One can verify that when the numerator is negative (i.e., $(1+c_g)(t''_{qq} - t''_{qk} \cdot t'_q/t'_k) < (1/q)[p' - (1+c_g)t'_q]$), we have $\mathrm{d}t/\mathrm{d}k > 0$, which implies that the average congestion delay will increase with the marginal capacity expansion; when the numerator is positive (i.e., $(1+c_g)(t''_{qq} - t''_{qk} \cdot t'_q/t'_k) > (1/q)[p' - (1+c_g)t'_q]$), we have $\mathrm{d}t/\mathrm{d}k < 0$. This completes the proof.

*Appendix A.6. Proof of Proposition 4.5*

The denominators of Eqs. (62) and (63) are the same, and are negative according to the second-order condition $\partial^2\mathcal{L}/\partial\rho^2 < 0$. Given $t'_k < 0, t''_{qk} \leqslant 0$, $c_g > 0$, and $q \geqslant 0$, the numerator of Eq. (62) is negative. Thus, we have $\mathrm{d}q/\mathrm{d}k > 0$, i.e., traffic volume will increase with the marginal capacity expansion. The sign of $\mathrm{d}t/\mathrm{d}k$ is up to its numerator. One can verify that when the numerator is negative (i.e., $(1+c_g)(t''_{qq} - t''_{qk} \cdot t'_q/t'_k) < (1/q)[p' + \frac{\mu}{1+\mu}(p''q + p') - (1+c_g)t'_q]$), we have $\mathrm{d}t/\mathrm{d}k > 0$, which implies that the average congestion delay will increase with the marginal capacity expansion; when the numerator is positive (i.e., $(1+c_g)(t''_{qq} - t''_{qk} \cdot t'_q/t'_k) > (1/q)[p' + \frac{\mu}{1+\mu}(p''q + p') - (1+c_g)t'_q]$), we have $\mathrm{d}t/\mathrm{d}k < 0$. This completes the proof.

## Appendix B. Proof of the total traffic volume is larger in leader-follower market than in Cournot market

According to Eq. (13), the output of the Cournot market with two airlines (i.e., $m = 2$) in the perfect substitutes scenario can be given by

$$q_1 = arg\left\{\rho + c_f = \frac{1}{2}q\left[p' - (1+c_g)t'_q\right] + \left[p - (1+c_g)t\right]\right\}. \tag{B.1}$$

Similarly, according to Eqs. (22) and (25), the output of the leader-follower market in the perfect substitutes scenario can be given by

$$q_2 = arg\left\{\rho + c_f = \frac{1}{2}q\left[p' - (1+c_g)t'_q\right] + \left[p - (1+c_g)t\right] + \frac{\lambda}{4+2\lambda}q\left[p' - (1+c_g)t'_q\right]\right\}. \tag{B.2}$$

Let $f(q) = \frac{1}{2}q[p' - (1+c_g)t'_q] + [p - (1+c_g)t]$ and $z(q) = \frac{\lambda}{4+2\lambda}q[p' - (1+c_g)t'_q]$. One can verify that $f(q)$ is a decreasing function of $q$. Given $\lambda \in (-1, -1/2)$, $p' < 0$ and $t'_q > 0$, we have $z(q) > 0$. We consider that these two airline markets are in the same airport setting and have the same costs (i.e., same $k, \rho, c_g, c_f$). Thus, we have

$$\rho + c_f = f(q_1) = f(q_2) + z(q_2). \tag{B.3}$$

Since $z(q_2) > 0$ and $f(q)$ is a decreasing function of $q$, we have $f(q_1) > f(q_2)$ and $q_1 < q_2$, i.e., the total output in the leader-follower market is larger than in the Cournot market.

## Appendix C. The derivations for key equations

### *Appendix C.1. The derivations for Eqs.* (15a) *and* (15b)

Taking partial derivatives of both sides of $\partial\pi_i/\partial q_i = 0$ with respect to $k$ yields

$$\left[p'' - (1+c_g)t''_{qq}\right]\frac{\partial q}{\partial k}q_i - (1+c_g)t''_{qk}q_i + \left[p' - (1+c_g)t'_q\right]\frac{\partial q_i}{\partial k} + \left[p' - (1+c_g)t'_q\right]\frac{\partial q}{\partial k} - (1+c_g)t'_k = 0.$$

Summing up all $i$ derives

$$\begin{aligned}
&\left[p'' - (1+c_g)t''_{qq}\right]\frac{\partial q}{\partial k}q - (1+c_g)t''_{qk}q + \left[p' - (1+c_g)t'_q\right]\frac{\partial q}{\partial k} + m\left[p' - (1+c_g)t'_q\right]\frac{\partial q}{\partial k} - m(1+c_g)t'_k = 0,\\
&\frac{\partial q}{\partial k} = \frac{(1+c_g)(t''_{qk}q + mt'_k)}{\left[p'' - (1+c_g)t''_{qq}\right]q + (m+1)\left[p' - (1+c_g)t'_q\right]}.
\end{aligned}$$

Thus, we obtain Eq. (15a).

Similarly, taking partial derivatives of both sides of $\partial\pi_i/\partial q_i = 0$ with respect to $\rho$ yields

$$\left[p'' - (1+c_g)t''_{qq}\right]\frac{\partial q}{\partial \rho}q_i + \left[p' - (1+c_g)t'_q\right]\frac{\partial q_i}{\partial \rho} + \left[p' - (1+c_g)t'_q\right]\frac{\partial q}{\partial \rho} - 1 = 0.$$

Summing up all $i$ derives

$$\begin{aligned}
&\left[p'' - (1+c_g)t''_{qq}\right]\frac{\partial q}{\partial \rho}q + \left[p' - (1+c_g)t'_q\right]\frac{\partial q}{\partial \rho} + m\left[p' - (1+c_g)t'_q\right]\frac{\partial q}{\partial \rho} - m = 0,\\
&\frac{\partial q}{\partial \rho} = \frac{m}{\left[p'' - (1+c_g)t''_{qq}\right]q + (m+1)\left[p' - (1+c_g)t'_q\right]}.
\end{aligned}$$

Thus, we obtain Eq. (15b).

### *Appendix C.2. The derivations for Eqs.* (27a), (27b) *and* (A.1)

Taking partial derivatives of both sides of $\partial\pi_\ell/\partial q_\ell = 0$ with respect to $k$ yields

$$\begin{aligned}
&\left[p'' - (1+c_g)t''_{qq}\right]\frac{\partial q}{\partial k}q_\ell(1+\lambda) + \left[p' - (1+c_g)t'_q\right]\left[\frac{\partial q_\ell}{\partial k}(1+\lambda) + q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}\right]\\
&\qquad + \left[p' - (1+c_g)t'_q\right]\frac{\partial q}{\partial k} - (1+c_g)\left[t''_{qk}q_\ell(1+\lambda) + t'_k\right] = 0,
\end{aligned}$$

where

$$\frac{\partial q}{\partial k} = \frac{\partial q_\ell}{\partial k} + \frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial k} = (1+\lambda)\frac{\partial q_\ell}{\partial k}.$$

Then, we have

$$\left[p'' - (1+c_g)t''_{qq}\right]\frac{\partial q}{\partial k}q_\ell(1+\lambda) - (1+c_g)t''_{qk}q_\ell(1+\lambda) + \left[p' - (1+c_g)t'_q\right]\left(2\frac{\partial q}{\partial k} + q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}\right) - (1+c_g)t'_k = 0,$$

$$\frac{\partial q}{\partial k} = \frac{(1+c_g)\left[t''_{qk}q_\ell(1+\lambda) + t'_k\right] - \left[p' - (1+c_g)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}}{\left[p'' - (1+c_g)t''_{qq}\right]q_\ell(1+\lambda) + 2\left[p' - (1+c_g)t'_q\right]}.$$

Thus, we obtain Eq. (27a).

Similarly, taking partial derivatives of both sides of $\partial\pi_\ell/\partial q_\ell = 0$ with respect to $\rho$ yields

$$\left[p'' - (1+c_g)t''_{qq}\right]\frac{\partial q}{\partial \rho}q_\ell(1+\lambda) + \left[p' - (1+c_g)t'_q\right]\left[\frac{\partial q_\ell}{\partial \rho}(1+\lambda) + q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}\rho} + \frac{\partial q}{\partial \rho}\right] - 1 = 0,$$

where

$$\frac{\partial q}{\partial \rho} = \frac{\partial q_\ell}{\partial \rho} + \frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial \rho} = (1+\lambda)\frac{\partial q_\ell}{\partial \rho}.$$

Then, we have

$$\left[p'' - (1+c_g)t''_{qq}\right]\frac{\partial q}{\partial \rho}q_\ell(1+\lambda) + \left[p' - (1+c_g)t'_q\right]\left(2\frac{\partial q}{\partial \rho} + q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}\rho}\right) - 1 = 0,$$

$$\frac{\partial q}{\partial \rho} = \frac{1 - \left[p' - (1+c_g)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}\rho}}{\left[p'' - (1+c_g)t''_{qq}\right]q_\ell(1+\lambda) + 2\left[p' - (1+c_g)t'_q\right]}.$$

Thus, we obtain Eq. (27b). Further simplify the term $\mathrm{d}\lambda/\,\mathrm{d}\rho$ in Eq. (27b) as follows:

$$\frac{\mathrm{d}\lambda}{\mathrm{d}\rho} = \frac{\mathrm{d}\lambda}{\mathrm{d}q_\ell}\frac{\partial q_\ell}{\partial \rho}.$$

Then, Eq. (27b) can be simplified as follows:

$$\frac{\partial q}{\partial \rho} = \frac{1}{\left[p'' - (1+c_g)t''_{qq}\right]q_\ell(1+\lambda) + \left[p' - (1+c_g)t'_q\right]\left[2 + q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}q_\ell}\cdot 1/(1+\lambda)\right]}.$$

Thus, we obtain Eq. (A.1).

*Appendix C.3. The derivations for Eqs.* (40a) *and* (40b)

Taking partial derivatives of both sides of $\partial\pi_\ell/\partial q_\ell = 0$ with respect to $k$ yields

$$\left\{\frac{\mathrm{d}p'_{\ell(\ell)}}{\mathrm{d}k} + \frac{\mathrm{d}p'_{\ell(f)}}{\mathrm{d}k}\lambda + p'_{\ell(f)}\frac{\mathrm{d}\lambda}{\mathrm{d}k} - (1+c_g)\left[\left(t''_{qq}\frac{\partial q}{\partial k} + t''_{qk}\right)(1+\lambda) + t'_q\frac{\mathrm{d}\lambda}{\mathrm{d}k}\right]\right\}q_\ell$$
$$+ \left[p'_{\ell(\ell)} + p'_{\ell(f)}\lambda - (1+c_g)t'_q(1+\lambda)\right]\frac{\partial q_\ell}{\partial k} + \frac{\mathrm{d}p_\ell}{\mathrm{d}k} - (1+c_g)\left(t'_q\frac{\partial q}{\partial k} + t'_k\right) = 0,$$

where

$$\frac{\mathrm{d}p'_{\ell(\ell)}}{\mathrm{d}k} = \frac{\partial p'_{\ell(\ell)}}{\partial q_\ell}\frac{\partial q_\ell}{\partial k} + \frac{\partial p'_{\ell(\ell)}}{\partial q_f}\frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial k} = (p''_{\ell(\ell\ell)} + \lambda p''_{\ell(\ell f)})\frac{\partial q_\ell}{\partial k},$$
$$\frac{\mathrm{d}p'_{\ell(f)}}{\mathrm{d}k} = \frac{\partial p'_{\ell(f)}}{\partial q_\ell}\frac{\partial q_\ell}{\partial k} + \frac{\partial p'_{\ell(f)}}{\partial q_f}\frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial k} = (p''_{\ell(f\ell)} + \lambda p''_{\ell(ff)})\frac{\partial q_\ell}{\partial k},$$
$$\frac{\mathrm{d}p_\ell}{\mathrm{d}k} = \frac{\partial p_\ell}{\partial q_\ell}\frac{\partial q_\ell}{\partial k} + \frac{\partial p_\ell}{\partial q_f}\frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial k} = (p'_{\ell(\ell)} + \lambda p'_{\ell(f)})\frac{\partial q_\ell}{\partial k},$$
$$\frac{\partial q}{\partial k} = \frac{\partial q_\ell}{\partial k} + \frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial k} = (1+\lambda)\frac{\partial q_\ell}{\partial k}.$$

Then, we have

$$\frac{\partial q}{\partial k}\left\{\left[\frac{p''_{\ell(\ell\ell)} + \lambda p''_{\ell(\ell f)} + \lambda p''_{\ell(f\ell)} + \lambda^2 p''_{\ell(ff)}}{(1+\lambda)^2} - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + \frac{2}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right] + \frac{2\lambda}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right]\right\} - (1+c_g)\left[t''_{qk}(1+\lambda)q_\ell + t'_k\right] + \frac{\mathrm{d}\lambda}{\mathrm{d}k}\left[p'_{\ell(f)} - (1+c_g)t'_q\right]q_\ell = 0,$$

$$\frac{\partial q}{\partial k} = \frac{(1+c_g)\left[t''_{qk}(1+\lambda)q_\ell + t'_k\right] - \left[p'_{\ell(f)} - (1+c_g)t'_q\right]q_\ell\frac{\mathrm{d}\lambda}{\mathrm{d}k}}{\left[\frac{p''_{\ell(\ell\ell)} + \lambda p''_{\ell(\ell f)} + \lambda p''_{\ell(f\ell)} + \lambda^2 p''_{\ell(ff)}}{(1+\lambda)^2} - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + \frac{2}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right] + \frac{2\lambda}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right]}.$$

By denoting $\delta = [p''_{\ell(\ell\ell)} + p''_{\ell(\ell f)}\lambda + p''_{\ell(f\ell)}\lambda + p''_{\ell(ff)}\lambda^2]/(1+\lambda)^2$, we obtain Eq. (40a).

Similarly, taking partial derivatives of both sides of $\partial\pi_\ell/\partial q_\ell = 0$ with respect to $\rho$ yields

$$\left\{\frac{\mathrm{d}p'_{\ell(\ell)}}{\mathrm{d}\rho} + \frac{\mathrm{d}p'_{\ell(f)}}{\mathrm{d}\rho}\lambda + p'_{\ell(f)}\frac{\mathrm{d}\lambda}{\mathrm{d}\rho} - (1+c_g)\left[t''_{qq}\frac{\partial q}{\partial\rho}(1+\lambda) + t'_q\frac{\mathrm{d}\lambda}{\mathrm{d}\rho}\right]\right\}q_\ell + \left[p'_{\ell(\ell)} + p'_{\ell(f)}\lambda - (1+c_g)t'_q(1+\lambda)\right]\frac{\partial q_\ell}{\partial\rho} + \frac{\mathrm{d}p_\ell}{\mathrm{d}\rho} - (1+c_g)t'_q\frac{\partial q}{\partial\rho} - 1 = 0,$$

where

$$\frac{\mathrm{d}p'_{\ell(\ell)}}{\mathrm{d}\rho} = \frac{\partial p'_{\ell(\ell)}}{\partial q_\ell}\frac{\partial q_\ell}{\partial\rho} + \frac{\partial p'_{\ell(\ell)}}{\partial q_f}\frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial\rho} = (p''_{\ell(\ell\ell)} + \lambda p''_{\ell(\ell f)})\frac{\partial q_\ell}{\partial\rho},$$
$$\frac{\mathrm{d}p'_{\ell(f)}}{\mathrm{d}\rho} = \frac{\partial p'_{\ell(f)}}{\partial q_\ell}\frac{\partial q_\ell}{\partial\rho} + \frac{\partial p'_{\ell(f)}}{\partial q_f}\frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial\rho} = (p''_{\ell(f\ell)} + \lambda p''_{\ell(ff)})\frac{\partial q_\ell}{\partial\rho},$$
$$\frac{\mathrm{d}p_\ell}{\mathrm{d}\rho} = \frac{\partial p_\ell}{\partial q_\ell}\frac{\partial q_\ell}{\partial\rho} + \frac{\partial p_\ell}{\partial q_f}\frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial\rho} = (p'_{\ell(\ell)} + \lambda p'_{\ell(f)})\frac{\partial q_\ell}{\partial\rho},$$
$$\frac{\partial q}{\partial\rho} = \frac{\partial q_\ell}{\partial\rho} + \frac{\partial q_f}{\partial q_\ell}\frac{\partial q_\ell}{\partial\rho} = (1+\lambda)\frac{\partial q_\ell}{\partial\rho}.$$

Then, we have

$$\frac{\partial q}{\partial\rho}\left\{\left[\frac{p''_{\ell(\ell\ell)} + \lambda p''_{\ell(\ell f)} + \lambda p''_{\ell(f\ell)} + \lambda^2 p''_{\ell(ff)}}{(1+\lambda)^2} - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + \frac{2}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right] + \frac{2\lambda}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right]\right\} - 1 + \frac{\mathrm{d}\lambda}{\mathrm{d}\rho}\left[p'_{\ell(f)} - (1+c_g)t'_q\right]q_\ell = 0,$$

$$\frac{\partial q}{\partial \rho} = \frac{1 - \left[p'_{\ell(f)} - (1+c_g)t'_q\right] q_\ell \frac{\mathrm{d}\lambda}{\mathrm{d}\rho}}{\left[\frac{p''_{\ell(\ell\ell)} + \lambda p''_{\ell(\ell f)} + \lambda p''_{\ell(f\ell)} + \lambda^2 p''_{\ell(ff)}}{(1+\lambda)^2} - (1+c_g)t''_{qq}\right](1+\lambda)q_\ell + \frac{2}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right] + \frac{2\lambda}{1+\lambda}\left[p'_{\ell(\ell)} - (1+c_g)t'_q\right]}.$$

By denoting $\delta = [p''_{\ell(\ell\ell)} + p''_{\ell(\ell f)}\lambda + p''_{\ell(f\ell)}\lambda + p''_{\ell(ff)}\lambda^2]/(1+\lambda)^2$, we obtain Eq. (40b).

*Appendix C.4. The derivations for Eqs.* (45) *and* (46)

Taking derivatives of both sides of $\partial\Pi/\partial\rho = 0$ with respect to $k$ yields

$$\frac{\mathrm{d}q}{\mathrm{d}k} + \frac{\mathrm{d}\rho}{\mathrm{d}k}\frac{\partial q}{\partial \rho} + (\rho + r - c_q)\frac{\mathrm{d}(\frac{\partial q}{\partial \rho})}{\mathrm{d}k} = 0,$$

where

$$\frac{\mathrm{d}(\frac{\partial q}{\partial \rho})}{\mathrm{d}k} = \frac{-\left[p'' - (1+c_g)t''_{qq}\right]\frac{\mathrm{d}q}{\mathrm{d}k} + (1+c_g)t''_{qk}}{\left[p' - (1+c_g)t'_q\right]^2},$$

$$\frac{\mathrm{d}q}{\mathrm{d}k} = \frac{\partial q}{\partial k} + \frac{\partial q}{\partial \rho}\frac{\mathrm{d}\rho}{\mathrm{d}k}.$$

By substituting Eqs. (11a),(11b) and (44), we have

$$\frac{\mathrm{d}\rho}{\mathrm{d}k}\left\{q\left[p'' - (1+c_g)t''_{qq}\right] + 2\left[p' - (1+c_g)t'_q\right]\right\} + \left[p' - (1+c_g)t'_q\right](1+c_g)(t'_k - qt''_{qk}) + q\left[p'' - (1+c_g)t''_{qq}\right](1+c_g)t'_k = 0.$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}k} = -(1+c_g)t'_k + \frac{\left[p' - (1+c_g)t'_q\right](1+c_g)(t'_k + qt''_{qk})}{q\left[p'' - (1+c_g)t''_{qq}\right] + 2\left[p' - (1+c_g)t'_q\right]}.$$

Thus, we obtain Eq. (45). Then, substituting Eq. (45) into

$$\frac{\mathrm{d}q}{\mathrm{d}k} = \frac{\partial q}{\partial k} + \frac{\partial q}{\partial \rho}\frac{\mathrm{d}\rho}{\mathrm{d}k},$$

we have

$$\frac{\mathrm{d}q}{\mathrm{d}k} = \frac{(1+c_g)(t'_k + qt''_{qk})}{q\left[p'' - (1+c_g)t''_{qq}\right] + 2\left[p' - (1+c_g)t'_q\right]}.$$

Thus, we obtain Eq. (46).

## References


Brueckner, J. K. (2002). Airport congestion when carriers have market power. *The American Economic Review*, *92*, 1357–1375.

Brueckner, J. K. (2003). Airline traffic and urban economic development. *Urban Studies*, *40*, 1455–1469.

Brueckner, J. K., & Van Dender, K. (2008). Atomistic congestion tolls at concentrated airports? Seeking a unified view in the internalization debate. *Journal of Urban Economics*, *64*, 288–295.

Brueckner, J. K., & Verhoef, E. T. (2010). Manipulable congestion tolls. *Journal of Urban Economics*, *67*, 315–321.

Bulow, J. I., Geanakoplos, J. D., & Klemperer, P. D. (1985). Multimarket oligopoly: Strategic substitutes and complements. *Journal of Political Economy*, *93*, 488–511.

Czerny, A. I., & Zhang, A. (2011). Airport congestion pricing and passenger types. *Transportation Research Part B: Methodological*, *45*, 595–604.

Czerny, A. I., & Zhang, A. (2014). Airport congestion pricing when airlines price discriminate. *Transportation Research Part B: Methodological*, *65*, 77–89.

De Neufville, R., Odoni, A. R., Belobaba, P. P., & Reynolds, T. G. (2013). *Airport systems: Planning, design, and management*. McGraw-Hill Education.
Dray, L. (2020). An empirical analysis of airport capacity expansion. *Journal of Air Transport Management*, *87*, 101850.
Duranton, G., & Turner, M. A. (2011). The fundamental law of road congestion: Evidence from US cities. *American Economic Review*, *101*, 2616–52.
Fageda, X., & Fernández-Villadangos, L. (2009). Triggering competition in the Spanish airline market: The role of airport capacity and low-cost carriers. *Journal of Air Transport Management*, *15*, 36–40.
Francis, G., Humphreys, I., & Ison, S. (2004). Airports' perspectives on the growth of low-cost airlines and the remodeling of the airport–airline relationship. *Tourism Management*, *25*, 507–514.
Fu, X., Homsombat, W., & Oum, T. H. (2011). Airport–airline vertical relationships, their effects and regulatory policy implications. *Journal of Air Transport Management*, *17*, 347–353.
Fu, X., Lijesen, M., & Oum, T. H. (2006). An analysis of airport pricing and regulation in the presence of competition between full service airlines and low cost carriers. *Journal of Transport Economics and Policy*, *40*, 425–447.
Fu, X., Tsui, K. W. H., Sampaio, B., & Tan, D. (2021). Do airport activities affect regional economies? Regional analysis of New Zealand's airport system. *Regional Studies*, *55*, 707–722.
Fukui, H. (2010). An empirical analysis of airport slot trading in the United States. *Transportation Research Part B: Methodological*, *44*, 330–357.
Gibbons, S., & Wu, W. (2017). Airports, market access and local economic performance: Evidence from China. *Journal of Economic Geography*, *20*, 903–937.
Gopalakrishnan, K., & Balakrishnan, H. (2021). Control and optimization of air traffic networks. *Annual Review of Control, Robotics, and Autonomous Systems*, *4*, 397–424.
Graham, D. J. (2007). Agglomeration, productivity and transport investment. *Journal of Transport Economics and Policy*, *41*, 317–343.
Graham, D. J., McCoy, E. J., & Stephens, D. A. (2014). Quantifying causal effects of road network capacity expansions on traffic volume and density via a mixed model propensity score estimator. *Journal of the American Statistical Association*, *109*, 1440–1449.
Graham, D. J., & Van Dender, K. (2011). Estimating the agglomeration benefits of transport investments: Some tests for stability. *Transportation*, *38*, 409–426.
Hansen, M. (1990). Airline competition in a hub-dominated environment: An application of noncooperative game theory. *Transportation Research Part B: Methodological*, *24*, 27–43.
Jiang, C., D'Alfonso, T., & Wan, Y. (2017). Air-rail cooperation: Partnership level, market structure and welfare implications. *Transportation Research Part B: Methodological*, *104*, 461–482.
Jiang, C., & Zhang, A. (2014). Effects of high-speed rail and airline cooperation under hub airport capacity constraint. *Transportation Research Part B: Methodological*, *60*, 33–49.
Kidokoro, Y., Lin, M. H., & Zhang, A. (2016). A general-equilibrium analysis of airport pricing, capacity, and regulation. *Journal of Urban Economics*, *96*, 142–155.
Le, L., Donohue, G., & Chen, C.-H. (2004). Auction-based slot allocation for traffic demand management at Hartsfield Atlanta International Airport: A case study. *Transportation Research Record*, *1888*, 50–58.
Li, Z.-C., Tu, N., Fu, X., & Sheng, D. (2022). Modeling the effects of airline and high-speed rail cooperation on multi-airport systems: The implications on congestion, competition and social welfare. *Transportation Research Part B: Methodological*, *155*, 448–478.
Lin, M. H. (2019). Airport congestion and capacity when carriers are asymmetric. *International Journal of Industrial Organization*, *62*, 273–290.
Liu, W.-J., Gong, X., & Li, Z.-C. (2022). Airport pricing and regulation under passenger demand uncertainty. *Transportmetrica B: Transport Dynamics*, *10*, 1184–1205.
Oum, T. H., & Fu, X. (2007). Air transport security user charge pricing: An investigation of flat per-passenger charge vs. Ad Valorem user charge schemes. *Transportation Research Part E: Logistics and Transportation Review*, *43*, 283–293.
Oum, T. H., & Fu, X. (2008). Impacts of airports on airline competition: Focus on airport performance and airport-airline vertical relations. *Joint Transport Research Centre, International Transport Forum, OECD*, .
Oum, T. H., & Zhang, Y. (1990). Airport pricing: Congestion tolls, lumpy investment, and cost recovery. *Journal of Public Economics*, *43*, 353–374.
Richard, O. (2003). Flight frequency and mergers in airline markets. *International Journal of Industrial Organization*, *21*, 907–922.
Sellner, R., & Nagl, P. (2010). Air accessibility and growth - The economic effects of a capacity expansion at Vienna International Airport. *Journal of Air Transport Management*, *16*, 325–329.
Takebayashi, M. (2015). Multiple hub network and high-speed railway: Connectivity, gateway, and airport leakage. *Transportation Research Part A: Policy and Practice*, *79*, 55–64.
Takebayashi, M. (2016). How could the collaboration between airport and high speed rail affect the market? *Transportation Research Part A: Policy and Practice*, *92*, 277–286.
Takebayashi, M. (2021). Workability of a multiple-gateway airport system with a high-speed rail network. *Transport Policy*, *107*, 61–71.
Tirole, J. (1988). *The theory of industrial organization*. MIT press.
Wan, Y., Jiang, C., & Zhang, A. (2015). Airport congestion pricing and terminal investment: Effects of terminal congestion, passenger types, and concessions. *Transportation Research Part B: Methodological*, *82*, 91–113.
Wang, K., Xia, W., Zhang, A., & Zhang, Q. (2018). Effects of train speed on airline demand and price: Theory and empirical evidence from a natural experiment. *Transportation Research Part B: Methodological*, *114*, 99–130.
Winston, C. (1991). Efficient transportation infrastructure policy. *The Journal of Economic Perspectives*, *5*, 113–127.
Xia, W., Jiang, C., Wang, K., & Zhang, A. (2019). Air-rail revenue sharing in a multi-airport system: Effects on traffic and social welfare. *Transportation Research Part B: Methodological*, *121*, 304–319.
Xia, W., & Zhang, A. (2016). High-speed rail and air transport competition and cooperation: A vertical differentiation approach. *Transportation Research Part B: Methodological*, *94*, 456–481.
Xiao, Y., Fu, X., Oum, T. H., & Yan, J. (2017). Modeling airport capacity choice with real options. *Transportation Research Part B: Methodological*,

*100*, 93–114.
Xiao, Y., Fu, X., & Zhang, A. (2013). Demand uncertainty and airport capacity choice. *Transportation Research Part B: Methodological*, *57*, 91–104.
Xiao, Y., Fu, X., & Zhang, A. (2016). Airport capacity choice under airport-airline vertical arrangements. *Transportation Research Part A: Policy and Practice*, *92*, 298–309.
Yang, H., & Fu, X. (2015). A comparison of price-cap and light-handed airport regulation with demand uncertainty. *Transportation Research Part B: Methodological*, *73*, 122–132.
Yang, H., & Zhang, A. (2011). Price-cap regulation of congested airports. *Journal of Regulatory Economics*, *39*, 293–312.
Yang, H., & Zhang, A. (2012). Effects of high-speed rail and air transport competition on prices, profits and welfare. *Transportation Research Part B: Methodological*, *46*, 1322–1333.
Zhang, A., Fu, X., & Yang, H. (2010). Revenue sharing with multiple airlines and airports. *Transportation Research Part B: Methodological*, *44*, 944–959.
Zhang, A., & Zhang, Y. (1997). Concession revenue and optimal airport pricing. *Transportation Research Part E: Logistics and Transportation Review*, *33*, 287–296.
Zhang, A., & Zhang, Y. (2003). Airport charges and capacity expansion: Effects of concessions and privatization. *Journal of Urban Economics*, *53*, 54–75.
Zhang, A., & Zhang, Y. (2006). Airport capacity and congestion when carriers have market power. *Journal of Urban Economics*, *60*, 229–247.
Zhang, A., & Zhang, Y. (2010). Airport capacity and congestion pricing with both aeronautical and commercial operations. *Transportation Research Part B: Methodological*, *44*, 404–413.
Zhang, F., & Graham, D. J. (2020). Air transport and economic growth: A review of the impact mechanism and causal relationships. *Transport Reviews*, *40*, 506–528.
Zhang, F., Lindsey, R., & Yang, H. (2016). The Downs–Thomson paradox with imperfect mode substitutes and alternative transit administration regimes. *Transportation Research Part B: Methodological*, *86*, 104–127.
Zhang, F., Yang, H., & Liu, W. (2014). The Downs–Thomson paradox with responsive transit service. *Transportation Research Part A: Policy and Practice*, *70*, 244–263.