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Hub airport slot Re-allocation and subsidy policy to speed up air traffic recovery amid COVID-19 pandemic --- case on the Chinese airline market

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ABSTRACT

With international air travels largely banned around the world amid the global COVID-19 pandemic, many gateway and hub airports have more ideal slots available for reallocation. Airport traffic recovery replaces airport congestion to become the primary challenge of major airports around the world. With the pandemic well controlled domestically in China, the government liberalizes the hub airport slots for those previously forbidden services to the small/regional airports. This paper thus analytically examines the effect of this slot liberalization. The government subsidy to the small airports has also been considered. It is found that the slot liberalization can speed up airport traffic recovery for both hub and small airports. The hub airport slot liberalization leads to a lower level of minimum subsidy to sustain the survival of the small airports. Given any fixed level of subsidy to the small airport, both the total airport traffic and social welfare would improve with the slot liberalization at the hub airport. When the government can adjust the level of subsidy after liberalizing the hub airport slots, the subsidy could be excessive, if the government emphasizes too much on airport traffic recovery. This would, however, harm the overall social welfare.

1. Introduction and background

The COVID-19 pandemic has brought unprecedented negative impact to the aviation industry. According to IATA (2020), the global air traffic for 2020 is expected to fall by 54.7% compared to 2019. Passenger throughput will roughly halve to 2.25 billion, approximately equal to 2006 levels. Passenger revenues are expected to fall to US$241 billion (dropped from US$612 billion in 2019). Overall, this is believed as the most serious crisis encountered by the airline industry in history. China, as the second largest airline market in the world, was also hit hard, especially in the first half of 2020. The first reported case of COVID-19 was documented in Wuhan, China. Many Chinese cities had been then locked down immediately, with most of the people quarantined at home in February and March (Huang et al., 2020; Zhang et al., 2020a). After the pandemic was well controlled since April, the Chinese airline market has gradually rebounded (Czerny et al., 2021). As shown in Fig. 1, such recovery is driven by the domestic markets, while the international markets are still under strict restriction in consideration of the high imported case risk brought by the still serious pandemic spread around the world (Oum and Wang, 2020; Zhang et al., 2020b). The prospect of the international airline market is quite gloomy and not expected to improve in the short term before the pandemic can be significantly contained globally. Many giant international airlines have encountered much deteriorating financial conditions, with some even going bankruptcy (Czerny et al., 2021). Many airports around the world are also faced with very difficult financial conditions with the risk to close operations (ACI Europe, 2020).

Among all Chinese airports, those hub airports have been more adversely affected, with serious traffic drop in both magnitude and percentage. Table A1 in Appendix 1 summarizes the passenger traffic change for major Chinese airports (with annual passenger throughput exceeding 10 million as of 2019). Beijing, Shanghai, and Guangzhou airports have been hub airports for China’s Big Three Airlines (i.e., Air China, China Eastern, and China Southern, respectively). These airports are also China’s gateways for international air travel, thus being hit the worst. The secondary and sizable Chinese airports were overall less impacted probably due to their smaller proportion of international traffic. For those small or regional Chinese airports having less than 2-
million annual passenger traffic (hereafter referred to as “small airports”), their throughputs were also significantly reduced due to the pandemic (as shown in Table A2 in Appendix 1). Small airports could face even more difficult financial conditions under dramatic traffic decline. Unlike the larger airports, these airports do not have enough capital reserve as they mainly live on government subsidies (Wang et al., 2017). With limited market size, they are less resilient to dramatic demand shock, probably taking a long time to fully recover.

China has 165 small airports (with an annual traffic passenger throughput of less than 2 million) accounting for 69% of the total number. Although their contribution to Chinese total air passenger traffic is limited, these small airports are important to guarantee essential transport services and to develop economies of the remote and less populous communities (Wang et al., 2017). According to the latest announced plan by the Civil Aviation Administration of China (CAAC), China aims to construct more than 200 new airports by 2035, with most of them being small airports. Thus, given the much less resilience but growing importance of these small airports in China’s airline market, it is vital to guarantee their survival and speed up their traffic recoveries. To mitigate COVID-19’s negative impact on these small airports, the Chinese government launched special subsidy programs as seen in Fig. 2. In particular, those small airports in Southwestern and Northern regions received more subsidy due to their more adverse traffic drop and importance to local communities.

In addition to direct monetary subsidy, CAAC considers granting small airports more access to the hub airports. As observed in Fu et al. (2015a) and Gong et al. (2018), most Chinese air traffics are concentrated at hub airports in Beijing, Shanghai, and Guangzhou. Unlike those liberalized airline markets (e.g., the US and Europe), the airport slots in large Chinese airports, especially the hub airports in Beijing, Shanghai and Guangzhou, have been tightly controlled by CAAC (Fu et al., 2015b). Chinese airline market was already largely liberalized in many aspects in the past three decades, such as airfare setting, fleet planning, airline ownership, etc. (Zhang and Round, 2008, 2011; Wang et al., 2018a). Since 2013, CAAC has also greatly lessened the airline route entry restrictions, allowing airlines to freely enter and exit any routes without a formal permit from CAAC. However, the airport slots in Beijing, Shanghai and Guangzhou are still tightly controlled by CAAC, and any route entry involved in these airports is subject to CAAC’s approval.

In particular, CAAC formally restricts any airline operation between small airports (less than 2-million annual passenger throughput) and hub airports in Beijing, Shanghai and Guangzhou, thus this market is commonly served by high-speed rail (HSR) (Jiang and Zhang, 2016; Jiang et al., 2017; Li et al., 2018; Wang et al., 2020).

Such slot allocation restrictions are justified with two major rationales. First, major Chinese airports suffered very serious congestion, requiring strict slot allocation control. As reported in Fu et al. (2020) and Tan et al. (2021), in 2017, the average flight arrival delay at Guangzhou Baiyun International Airport is 42.4 min; 46.1 min at Shanghai Pudong Airport; 47.9 min at Shanghai Hongqiao Airport; and 48 min at Beijing Capital Airport. This had become such a pressing issue that CAAC introduced a heavy-handed regulation on October 29, 2017. This policy introduced strict rules on capacity increases for slot-coordinated airports, and in some cases reduced the allowable capacities for airports that had an on-time performance (OTP) below 85% in the previous season. Airlines are also forced to cancel their flights that had repeatedly poor OTP. Second, the airline markets involved in the hub airports are the most lucrative in China. The time slots at these hub airports are scarce resources, mainly acquired by dominant airlines through “grandfather rules” (Sheng et al., 2015, 2019). The Big Three Airlines are largely state-owned and are based at these hub airports. CAAC is thus intended to restrict new market entries at these hub airports, especially preventing those private or low-cost carriers (LCCs), in order to avoid fierce competition with these legacy carriers (Yang et al., 2020).

However, as discussed earlier, Chinese major hub airports have seen a more dramatic traffic drop due to the COVID-19 pandemic, especially with the international traffic difficult to rebound in the short run. Their airport congestion has been greatly alleviated, and more slot resources have been released for possible re-allocations.4 When most of the existing domestic routes at the hub airports have yet achieved the traffic level before the pandemic, it would be feasible to assign the newly available slots to serve those small airports that have originally been banned. Moreover, the services to these small airports are mainly offered by the private airlines or local carriers, such that they will not impose head-to-head competition with the Big Three Airlines. That is, the Big Three Airlines’ recovery would not be largely harmed by opening up the hub airports to serve small airports.

On September 16, 2020, CAAC formally announced to remove the capacity constraint of the hub airports in Beijing, Shanghai and Guangzhou, and also eliminate restrictions for these hub airports to fly

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2 Please see CAAC’s formal policy to restrict services from hub airports to the small airports at the following link: https://news.carnoc.com/list/419/419046.html.

3 For example, to prevent head-to-head competition with Big Three Airlines, CAAC rejected Spring Airlines’ (i.e., China’s largest LCC) application to serve Beijing Capital Airport, although Spring Airlines insisted to apply for the slots for six years since its inauguration. CAAC eventually assigned one slot to Spring Airlines in the midnight at Beijing Capital Airport, and Spring Airlines finally gave up that slot due to lack of demand at such inconvenient time (Fu et al., 2018b).

4 The passenger traffic of Beijing, Shanghai and Guangzhou airports decreased by more than half in the first half of the year. See the detailed contents at the following link: http://news.carnoc.com/list/543/543801.html. The on-time performance of the major Chinese airports are also improved due to the traffic reduction. Thus, the airport congestion would not be an major issue to re-allocate the international flight slots.
to small airports.\(^5\) This policy marks a significant step in the liberalization of China’s airline market. For the first time, Chinese airlines are granted the freedom to acquire slots and freely decide route entries involved in the hub airports in Beijing, Shanghai and Guangzhou. CAAC’s new policy can be summarized in the following two main points:

1. Lifting the weekly maximum frequency of 49 busy routes involved Beijing, Shanghai and Guangzhou. Airlines can freely decide frequencies according to market demand conditions;  
2. Airlines can apply for slots in Beijing, Shanghai and Guangzhou to serve small airports with annual passenger throughput less than 1 million, as long as the airlines operate at least 15 routes from the hub airports.

This new CAAC policy targets to speed up China’s airline market recovery, in particular for a large number of small airports. It is also one remarkable step in China’s airline market liberalization. This study thus aims to build an economic model with a simplified airline network, analytically examining the effect of such policy on the airline market outcomes, including airline route entry decisions, airport throughputs (both hub and small airports), airfares, and the social welfare. The results could provide a comprehensive evaluation of the policy’s effects and mechanisms to speed up air traffic recovery in China. Specifically, liberalizing slots at the hub airport can increase air traffic at both the hub and small airports, thus speeding up airport traffic recovery, *ceteris paribus*. The airline operating based at the small airport can have higher profit by entering the routes between the small and hub airports, while the profit of the legacy carriers based at the hub airport would not necessarily be negatively affected. As a result, the minimum level of CAAC subsidy is lower to sustain the survival of the small airports after the slot liberalization at the hub airports. Given any fixed level of subsidy to the small airport, both the total airport traffic and social welfare would improve after slot liberalization at the hub airport. In addition, when CAAC can adjust its subsidy to small airports together with the decision on hub airport slot liberalization, the optimal subsidy level depends on the relative weight that CAAC puts on the airport traffic recovery and social welfare maximization. CAAC would provide a higher subsidy to small airports after liberalizing hub airport slots, because of the higher marginal gain in total airport traffic. However, when CAAC emphasizes too much on airport traffic recovery, the subsidy could be too much excessive, harming the overall social welfare due to its shadow price of the public fund spending.

This paper has multi-fold contributions. First, it provides an analytical evaluation of China’s hub airport slot allocation liberalization on the network-wise market outcomes. Second, we predict the outcomes of such a new policy on the airport traffic for both the small and the hub airports, thus evaluating its effects to speed up airline market recovery. Last, our discussions based on the Chinese contexts also offer useful policy implications for other markets that also have a sizable domestic market (e.g., the US and European Union). Although other major airline markets are overall more liberalized, many of their gateway/hub airports have also been subject to tight slot control (i.e., the slot-coordinated airports). For example, four US airports have slots strictly controlled by FAA (Federal Aviation Administration), including John F. Kennedy International Airport (JFK), LaGuardia Airport (LGA), and Ronald Reagan Washington National Airport (DCA) (Fukui, 2010). The major EU gateway airports are also categorized as slot-coordinated airports, including the London Heathrow (LHR), Paris Charles De Gaulle (CDG), Amsterdam Schiphol (AMS), etc. When the international air traffic has been largely banned, these airports have also newly available slots ready to be re-allocated. Our analyses thus suggest that, when the pandemic is better controlled domestically, allocating these hub airport slots in favor of serving those underserved small airports could be a welfare-improving measure, which helps speed up traffic recovery of both the hub and small airports. Such a slot reallocation could interact with the existing subsidy programs provided by the US and European governments to the small and regional airports, which would better facilitate the air traffic recovery.\(^6\)

This paper is organized as follows. Section 2 introduces our basic economic model setup, which is based on a simplified airline network consisted of both hub and small airports. The analytical results and relevant policy implications are provided in Section 3. Section 4 discusses the change in optimal subsidies when CAAC can adjust the subsidy level and how it affects the overall social welfare. Then, the last section concludes the study.

2. The economic model setup

In this section, we establish an analytical model with a simplified airline network in China, which is consisted of one hub airport, one small airport and a third airport. As shown in Fig. 3, City A is a small city with a small Airport A (i.e., the passenger traffic volume is less than 2 million) and also a high-speed rail (HSR) station. City B is one of the three major hub airports in Beijing, Shanghai or Guangzhou. City C is a relatively distant city from City A and City B, such that it is connected with City A and City B with airline service. One legacy airline (i.e., Airline 1) operates the route between City B and City C (hereafter referred to as Market BC). Another airline (i.e., Airline 2) operates the route between City A and City B (hereafter referred to as Market AB). Airline 2 could be a private airline or local airline owned by the municipal government, which prefers serving the small Airport A, for example, Spring Airlines.\(^7\)

As mentioned in the introduction, CAAC originally forbade the airline service from the hub Airport B to small Airport A (hereafter referred to as Market AB), such that this market can only be served by HSR. In addition, the origin-destination (OD) passenger for Market AC can also choose the air-HSR transfer service by taking the HSR from City B to City A, and then taking Airline 2 from City A to City C. Because the traffic demand in Market AC could be small, the government thus has to provide subsidy to the flights at the small Airport A.

With the serious decline of intercity travel demand amid the COVID-19 pandemic, the Chinese government has to offer more subsidies to the

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\(^5\) See the detailed contents of the policy at CAAC official website: https://www.caac.gov.cn/XWZX/MHYW/202009/20200916_204552.html (in Chinese).

\(^6\) The US government implements the “Essential Air Service (EAS)” program to provide subsidy to airlines to serve small communities to maintain a minimum level of scheduled air services. EU also has similar programs to subsidize regional airline services to the remote and small communities.

\(^7\) Spring Airlines is the largest private and low-cost carrier (LCC) in China. Although based in Shanghai, Spring Airlines mainly serve the secondary airports (small-sized airports) in China (Fu et al., 2015b; Wang et al., 2018a).
small Airport A to guarantee a minimum level of essential air services and maintain the survival of the airport. In addition, the new policy announced in September 2020 eliminated entry barriers at the hub airports to allow hub airport slots to be allocated to services with the small airport (i.e., airline service in Market AB). Our economic model aims to analyze market outcomes with and without such hub slot liberalization. We thus propose a two-stage game as below:

Stage 1: CAAC decides an optimal subsidy level and also decide whether to liberalize the slots at the hub Airport B.

Stage 2: Airline 2 decides whether to enter Market AB if CAAC liberalizes the slots at Airport B.

As the subsidy level is not very flexible to be adjusted by CAAC, we consider two cases. The first is the analysis of slot liberalization conditional on the given subsidy level which has been ex-ante stipulated (i.e., Section 2). Then, we advance the study by allowing CAAC to decide optimal subsidy and whether to liberalize the slots simultaneously (i.e., Section 4).

To quantify the intercity traffic in this network of Fig. 3, let us consider a representative passenger who decides his traffic in each OD market. Following Singh and Vives (1984), a quadratic consumer utility function is adopted for the representative passenger (Oum and Fu, 2007; Jiang and Zhang, 2014). Specifically, the utility function is expressed as the following Eq. (1).

\[
U = \alpha(q_1 + q_2 + q_1q_2 + \beta q_1 q_3 + q_2 q_3 + f_1 q_1 + f_2 q_2 + f_3 q_3 + f_4 q_4)
\]

where the parameter \( \alpha \) represents the potential intercity travel market sizes of the network. The COVID-19 pandemic would discourage the intercity traffic, reflected by a smaller \( \alpha \). \( q \) denotes the traffic on each different OD traffic. To simplify notations, we adopt different numerical numbers and letters as the subscripts for the traffic and ticket price in different OD traffic. To simplify notations, we adopt different numerical numbers and letters as the subscripts for the traffic and ticket price in different OD traffic. To simplify notations, we adopt different numerical numbers and letters as the subscripts for the traffic and ticket price in different OD traffic. To simplify notations, we adopt different numerical numbers and letters as the subscripts for the traffic and ticket price in different OD traffic. To simplify notations, we adopt different numerical numbers and letters as the subscripts for the traffic and ticket price in different OD traffic. To simplify notations, we adopt different numerical numbers and letters as the subscripts for the traffic and ticket price in different OD traffic. To simplify notations, we adopt different numerical numbers and letters as the subscripts for the traffic and ticket price in different OD traffic. To simplify notations, we adopt different numerical

\[
(1)
\]

The passenger surplus can be defined as follows by subtracting the total travel cost (including both monetary and time costs), where \( T \) is the transfer cost (i.e., time cost and other costs) via City A for OD passenger of Market BC.

\[
CS = U - p_1q_1 - p_2q_2 - p_3q_3 - p_4q_4 - Tq_4
\]

Then, the representative passenger maximizes the surplus by choosing the traffic in different OD markets (i.e., \( q_1, q_2, q_3, q_4 \) and \( q_5 \)). The first-order conditions (FOCs) lead to the following inverse demand functions.

For Market BC, the inverse demand function of Airline 1 is as follows,

\[
p_1 = \alpha + f_1 - q_1 - q_2
\]

When Airline 2 does not serve in Market AB, the inverse demand of transfer traffic of Market BC via City A is specified as follows,

\[
p_2 = \alpha + f_2 - q_2
\]

The inverse demand function of Airline 2 in Market AC is as follows,

\[
p_3 = \alpha + f_3 - q_1 - q_2
\]

Then, the representative passenger maximizes the surplus by choosing the traffic in different OD markets (i.e., \( q_1, q_2, q_3, q_4 \) and \( q_5 \)). The first-order conditions (FOCs) lead to the following inverse demand functions.

For Market BC, the inverse demand function of Airline 1 is as follows,

\[
p_1 = \alpha + f_1 - q_1 - q_2
\]

When Airline 2 does not serve in Market AB, the inverse demand of transfer traffic of Market BC via City A is specified as follows,

\[
p_2 = \alpha + f_2 - q_2
\]

The inverse demand function of Airline 2 in Market AC is as follows,

\[
p_3 = \alpha + f_3 - q_1 - q_2
\]

The inverse demands of HSR and Airline 2 in Market AB are derived as follows,

\[
p_5 = \alpha + f_3 - q_1 + \beta q_3 p_3' = \alpha + f_1 - q_1 - \beta q_1
\]

Regarding the operating costs, for simplicity, we normalize HSR’s marginal operating cost as zero. Analogous to Lin (2012), we capture airlines’ operating costs on the flight basis (e.g., taking off and landing fees, fuel cost and other flight-related costs). The airlines’ operating cost is thus denoted as \( r_f \) in the spirit of Brueckner (2004), Brueckner and Flores-Fillol (2007) and Lin (2012), where \( r \) is the flight cost parameter. Given the already complexity of analysis, the flight cost parameter \( r \) has been normalized to 1 to simplify the discussions. This normalization would not qualitatively alter our main conclusions. The total flight costs exhibit an increasing marginal flight cost as the operating cost, fleet coordination and airport congestion increase to a larger extent with the number of flights. Moreover, this model also allows the flight load factor to vary, which can be calculated by dividing the traffic by the corresponding frequency.

In addition, CAAC also provides the subsidy to flights serving the small Airport A as mentioned in the introduction. It is noted that the subsidy is offered directly to the airlines instead of the airports. The subsidy is at per-flight basis, such that the airlines collect a total subsidy in proportion to the number of flights operated at the small airports. Meanwhile, the airport charges in the Chinese airports are regulated to be fixed, not able to be freely adjusted by airports themselves. Thus the small airports benefit indirectly from an possible traffic increase from

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\[ \text{Table 1} \]

| Traffic and Ticket Price | AIRLINE 2 NOT ENTERING MARKET AB | AIRLINE 2 ENTERING MARKET AB |
|--------------------------|---------------------------------|------------------------------|
| OD                       | Traffic                        | Ticket Price                 |
| BC                       | \( q_1 \)                       | \( p_1' - a + f_1' - q_1' - q_2' \) |
|                          | \( q_2' \)                      | \( p_1' - a + f_1' + f_2' \) |
|                          | \( p_1' - q_1' - q_2' - T \)    | \( T - q_1' - q_2' \) |
| AC                       | \( p_2' - a + f_2' - q_1' \)    | \( p_2' - a + f_3' + f_4' \) |
|                          | \( q_3' \)                      | \( p_3' = a + f_3' - q_1' - q_2' \) |
|                          | \( q_4' \)                      | \( p_4' = a + f_3' + q_1' - q_2' \) |

---

\( ^2 \) Compared to Airline 2, Airline 1 is much less likely to enter Market AB with slot liberalization at Airport B. Market AB is a thin market, which could be subject to natural monopoly (i.e., not big enough to sustain two airlines). Airline 2, as a private and local airline already operating at small Airport A, could have cost advantage and emphasis to serve Market AB.

\( ^3 \) The subsidy for the small airports is jointly formulated by the China Ministry of Finance and CAAC according to the relevant regulations on the management rules of “Civil Aviation Development Fund”, and it is thus not very flexible to be adjusted in a short term.
the subsidized airlines.\footnote{In the alternative case where the subsidy is provided to the airports while allowing them to adjust the airport charge to airlines, the problem of double marginalization would emerge in that both airport and downstream airlines would charge a premium from the subsidy. Thus, the airlines would not reduce the airfare as much as the case where they directly receive the subsidy. Then, the airfare increase at these small airports would also be lower, weakening the effectiveness of the CAAC subsidy policy. Meanwhile, unlike airports that are mostly state-owned, Chinese airlines have more share of private ownership, thus are more vulnerable to traffic reduction amid pandemic. Imposing the subsidy directly upon the airlines would enable them to enjoy a larger share of financial benefit, which is ideal for the overall stability of Chinese airline industry. We appreciate one anonymous reviewer to raise the comment on the different effectiveness to subsidize airlines vs. airports, and to suggest such discussions.}

During the pandemic, the Chinese government offered a larger amount of subsidy to sustain the survival of these small airports. Since the subsidy policies had already been stipulated with detailed implementation plans before CAAC liberalized the hub airport slots (see Table A2), we first assume an exogenously given CAAC subsidy $\delta$ per flight at the small Airport A for the analysis (see Section 3). Then, in Section 4, we allow CAAC to adjust the subsidy $\delta$, and then derive and benchmark CAAC’s optimal subsidy level to the small airport Airport A and the corresponding equilibrium outcomes, with and without slot liberalization at the hub Airport B. For easy reference, the notation of the parameters have been collated in the following Table 2.

### Table 2
Notational glossary.

| Parameter | Definitions |
|-----------|-------------|
| $q$       | Traffic     |
| $p$       | ticket price|
| $f$       | Frequency   |
| $l$       | load factor |
| $\beta$   | substitutability of Airline and HSR services on Market AB with $0 < \beta < 1$ |
| $\alpha$  | potential market size of the intercity traffic network |
| $T$       | passenger’s transfer cost via City A |
| $\delta$  | subsidy per flight at Airport A |
| $\pi$     | Profit      |
| $CS$      | passenger surplus |
| $SW$      | social welfare |
| $\mu$     | the weight on the total airline traffic $Q$ in CAAC’s objective function with $0 < \mu < 1$ |
| $\Lambda$ | CAAC’s objective function value |

3. Analysis results

This section examines the market equilibrium for the intercity transport network as proposed in Section 2. Airlines and HSR operate the network conditional on CAAC’s already stipulated subsidy level to the flights serving small Airport A. Backward induction is adopted to solve the two-stage game proposed in Section 2. Specifically, in this section, we first solve for market equilibrium without the slot liberalization at the hub airport (i.e., Airport B) to serve the small airport (i.e., Airport A). This is a case where there is no airline service in Market AB. Then, we allow CAAC to adjust the subsidy $\delta$ (see Table A2), we first assume an exogenously given CAAC subsidy $\delta$ per flight at Airport A to survive, CAAC’s optimal subsidy level to the small airport Airport A, and the corresponding equilibrium outcomes, with and without slot liberalization at the hub Airport B. For easy reference, the notation of the parameters have been collated in the following Table 2.

#### 3.1. No airline service in market AB

When CAAC forbids airlines to serve the small airports out of the hub airports, there would be no airline services in Market AB. Therefore, Airline 1 operates direct flights in Market BC. Meanwhile, Airline 2 and HSR cooperate to serve the transfer passengers for OD Market BC via City A. As a result, Airline 1 and Airline 2 compete in Market BC. Market AB is, however, exclusively served by HSR, while Market AC is exclusively served by Airline 2. The profits for Airline 1, Airline 2 and HSR are expressed as below, respectively, with the superscript $n$ denoting the case of no airline service in Market AB.

\[
\begin{align*}
\text{Max } & \pi_1^n = p_1^n q_1^n - (f_1^n)^2 \\
\text{Max } & \pi_2^n = \left(p_2^n - p_2^m\right)q_2^n + p_2^m q_2^n - \left(f_2^n\right)^2 + \delta_2^n \bar{q}_2^n \\
\text{Max } & \pi_h^n = p_h^n q_h^n - \left(f_h^n\right)^2 \\
\end{align*}
\]

Then the equilibrium frequency, traffic, and ticket price for different airlines, HSR can be solved for different OD markets as below.

\[
\begin{align*}
\bar{f}_1^n &= \frac{7a + 6T - 2\delta}{21}, \\
\bar{q}_2^n &= \frac{14a - 3T + 8\delta}{7}, \\
\bar{p}_h^n &= \frac{14a + 4\delta - 14T}{21}. \\
\end{align*}
\]

The equilibrium profits for Airlines 1 and 2 are

\[
\bar{\pi}_1^n = \frac{(7a + 6T - 2\delta)^2}{147}, \quad \bar{\pi}_2^n = \frac{66(2T - \delta)^2 + 49(2a + \delta)^2 + 125\delta}{588}
\]

As observed from the expressions of $\bar{q}_2^n$ and $\bar{p}_h^n$, an increase in CAAC subsidy $\delta$ at the small Airport A would increase airline traffic at the small Airport A, but damage airline traffic at the hub Airport B. However, the total traffic of the two airports increases with the subsidy $\delta$. The non-negativity of the airline traffic at the small Airport A (i.e., $\bar{q}_2^n$) suggests that $\delta > \frac{\delta}{2} = \frac{1}{2}T - \alpha$. That is, in order to make sure that the small Airport A to survive, CAAC’s minimum subsidy should be at least $\delta = \frac{1}{2}T - \alpha$. Such a minimum subsidy has to increase with a decreasing $\alpha$. That is, when the intercity travel demand was seriously damaged by the COVID-19 pandemic, CAAC has to raise its minimum subsidy standard as well.

#### 3.2. Airline service available in market AB

After CAAC liberalizes slots at hub Airport B to serve small Airport A, Airline 2 can decide whether to enter Market AB. If it decides not to enter, the market structure and equilibrium would exactly be the same as those in Section 3.1. If Airline 2 enters Market AB, the profit functions of Airline 1, Airline 2 and HSR would be as below, with the superscript $e$ denoting the case of slot liberalization at the hub Airport B and entry of Airline 2 into Market AB.

\[
\begin{align*}
\text{Max } & \pi_1^e = p_1^e q_1^e - (f_1^e)^2 \\
\text{Max } & \pi_2^e = \left(p_2^e - p_2^m\right)q_2^e + p_2^m q_2^e - \left(f_2^e\right)^2 - \left(f_2^e\right)^2 + \delta_2^e \bar{q}_2^e \\
\text{Max } & \pi_h^e = p_h^e q_h^e - \left(f_h^e\right)^2 \\
\end{align*}
\]

Then, the equilibrium frequency, traffic, and price for different airlines, HSR can be solved for different OD markets as below.
\[\begin{align*}
\hat{f}_1 & = \frac{a(18 + 6\beta) - \beta^2(24T + 13\alpha - 14\delta) + 54T - 36\delta}{162 - 75\beta^2} - \hat{f}_a = \frac{(18 - 14\beta)\alpha + (37 - 8\delta)\beta}{54 - 25\beta^2} \\
\hat{f}_2 & = \frac{a(90 - 6\delta) - \beta^2(64\delta + 37\alpha - 24T) - 54T + 144\delta}{162 - 75\beta^2} \\
\hat{f}_3 & = \frac{2a(15 - 7\beta) - \beta^2(16\delta + 3\alpha - 6T) - 18T + 48\delta}{54 - 25\beta^2} \\
\hat{q}_1 & = \frac{12a(3 + \beta) - 2\beta^2(13\alpha + 24T - 14\delta) + 108T - 72\delta}{162 - 75\beta^2} - \hat{q}_a = \frac{(36 - 28\beta)\alpha + 2(37 - 8\delta)\beta}{54 - 25\beta^2} \\
\hat{q}_3 & = \frac{6a(6 - \delta) - 2\beta^2(78 + 6\alpha - 12T) - 54T + 36\delta}{54 - 25\beta^2} \\
\hat{p}_1 & = \frac{12a(3 + \beta) - 2\beta^2(13\alpha + 24T - 14\delta) + 108T - 72\delta}{162 - 75\beta^2} - \hat{p}_a = \frac{(40 - 7\beta)\alpha + 2(37 - 8\delta)\beta}{54 - 25\beta^2} \\
\hat{p}_3 & = \frac{6a(6 - \delta) - 2\beta^2(78 + 6\alpha - 12T) - 54T + 36\delta}{54 - 25\beta^2}
\end{align*}\]

The equilibrium profits for Airline 1, Airline 2 and HSR are

\[\begin{align*}
\hat{x}_1^* & = \left[\frac{(14\delta - 13\alpha - 24T)\beta^2 + 6a\beta - 54T - 36\delta + 18\alpha}{(54 - 25\beta^2)}\right]^2 \\
\hat{x}_2^* & = \frac{2\beta^2 \left[ a(497\alpha + 743\delta - 748T + 246T(6T - 7\delta) + 15908\delta) - 18\beta^2 \left[ a(175\alpha - 384T + 380\delta) + 72T(5T - 6\delta) + 392\delta \right] - 24a\beta^2 \left( 12T - 6\alpha - 7\delta \right) - 108a\beta(46\alpha - 15T + 28\delta) + 9072(\alpha + \delta) + 2430T(3T - 4\delta) - 1944\alpha(3\delta + 51T) \right]}{3(54 - 25\beta^2)^2} \\
\hat{x}_3^* & = \frac{3(37 - 8\delta - 14\alpha)\beta + 18\alpha}{(54 - 25\beta^2)^2}
\end{align*}\]

Similar to Section 3.1, as observed from the expressions of \(\hat{q}_1^*\) and \(\hat{q}_2^*\), we obtain the same qualitative findings: an increase in CAAC subsidy \(\delta\) at the small Airport A would benefit the airline traffic at Airport A, but damage airline traffic at hub Airport B. However, the sum of airline traffic of the two airports increases with \(\delta\). The non-negativity of \(\hat{q}_2^*\)

![Fig. 4. The profit difference of Airline 2, \(\Delta \hat{x}_2 (T = 1, \beta = 0.5)\).](image)

![Fig. 5. a. The airline traffic difference of airport A (\(T = 1, \beta = 0.5\)). b. The airline traffic difference of airport B (\(T = 1, \beta = 0.5\)).](image)
suggests that \( \delta > \delta^* = \frac{254 - 21 \beta^2}{254 - 21 \beta^2} T - \frac{36 - 2 \beta}{125 - 36 \beta} \alpha \). That is, in order to sustain the survival of the small Airport A, CAAC’s minimum subsidy should be \( \delta^* = \frac{254 - 21 \beta^2}{254 - 21 \beta^2} T - \frac{36 - 2 \beta}{125 - 36 \beta} \alpha \). When comparing the minimum subsidies with and without airline service on Market AB (i.e., \( \delta^* \) vs. \( \delta^* \)), we obtain Lemma 1.

**Lemma 1.** When CAAC liberalizes slots at the hub Airport B to serve the small Airport A, it needs a lower minimum level of subsidy to sustain the survival of the small Airport A. In addition, with the pandemic damaging the intercity travel demand, the minimum level of subsidy needs to be raised for the small Airport A.

Lemma 1 can be proved in that \( \delta^* - \delta^* = \frac{162 - 27 \beta^2}{254 - 21 \beta^2} T + \frac{108 - 18 \beta^2 - 36 \beta}{254 - 21 \beta^2} \alpha > 0 \). The entry of Airline 2 into Market AB can increase the traffic at Airport A from two sources. First, there would be newly generated airline traffic in Market AB. Second, Airline 2 is able to offer the interline service for OD Market BC by transferring from Airport A, without cooperating with HSR to serve the Market AB segment. This would help overcome the “double marginalization” issue (Xia et al., 2019), reducing the price of the transfer service and increasing the transfer traffic at Airport A. As a result, Airport A would have higher traffic with the slot liberalization at the hub Airport B given the same level of CAAC subsidy \( \delta \) (i.e., \( q^*_A > q^*_2 \)). In other words, Airport A needs a lower minimum subsidy with the slot liberalization at the hub Airport B.

Next, we examine whether Airline 2 would like to enter Market AB or not, if CAAC liberalizes the slots at the hub Airport B. This is to compare Airline 2’s equilibrium profits with and without entry into Market AB.

\[
\Delta l_1 = \frac{q^*_2}{s_2} - \frac{q^*_A}{s_1} = \frac{9}{90 - 3 \beta^2} \left[ (18 - 7 \beta^2 - 2 \beta) T - (18 - 8 \beta) \right] \gamma \left[ (90 - 3 \beta^2)^{-1} \right] \left[ (90 - 3 \beta^2) \alpha - 16 (9 - 4 \beta) \beta - 6 (9 - 4 \beta) \right] T + \frac{9}{90 - 3 \beta^2} \left[ (18 - 7 \beta^2 - 2 \beta) \right] \gamma \left[ (90 - 3 \beta^2)^{-1} \right] \left[ (90 - 3 \beta^2) \alpha - 16 (9 - 4 \beta) \beta - 6 (9 - 4 \beta) \right] \gamma T
\]

With the proof shown in Appendix 2, it is found that \( \bar{s}_2^* \geq \bar{s}_2^* \), which leads to Proposition 1.

**Proposition 1.** When CAAC liberalizes the slots at the hub Airport B to serve small Airport A and also maintains the level of subsidy, Airline 2 would prefer entering into Market AB (i.e., \( \bar{s}_2^* \geq \bar{s}_2^* \)).

Proposition 1 suggests that Airline 2 always has an incentive to enter Market AB as long as the slots at the hub airport are granted. We also have the additional comparative statics as \( \frac{d s_2^*}{d \beta} > 0 \), \( \frac{d s_2^*}{d \alpha} > 0 \) and \( \frac{ds_2^*}{ds_2^*} > 0 \). That is, Airline 2’s incentive to enter Market AB increases with the potential market size \( \alpha \) and CAAC’s subsidy \( \delta \). Therefore, when the intercity travel demand is recovering (i.e., a larger \( \alpha \)), we would expect Airline 2 is more motivated to utilize the slot liberalization at the hub Airport B by entering Market AB. Meanwhile, a higher subsidy \( \delta \) at the small Airport A also encourages Airline 2 to open airline services in Market AB in order to enjoy the subsidy, Market recovery and CAAC subsidy can strengthen each other’s positive effect on Airline 2’s incentive to enter Market AB. To better illustrate the above results, we also made Fig. 4.

CAAC liberalizes the slots at the hub Airport B in order to facilitate air traffic recovery for both the small Airport A and hub Airport B. We can thus evaluate the policy effect to improve airport traffic recovery by comparing the two airports’ traffic with and without slot liberalization at the hub Airport B (\( \hat{Q}_A, \hat{Q}_B \)). This leads to Proposition 2.

**Proposition 2.** The airline traffic of both the hub Airport B and the small Airport A would increase, when CAAC liberalizes the slots at the hub Airport B to serve the small Airport A (i.e., \( \bar{Q}_A^* > Q_A^* \) and \( \bar{Q}_B^* > Q_B^* \))

The proof of Proposition 2 can also be found in Appendix 2. To better illustrate the above results, we also made Fig. 5a and b. It is not difficult to draw a conclusion from the figures: regardless of whether it is the small airport A or the hub airport B, the difference in air traffic will gradually increase as the market recovers and the amount of subsidy increases after the liberalization of slots. Proposition 2 has important policy implications. The slot liberalization at hub airports not only benefits the survival of small airports, but also contributes to the recovery of the hub airports per se. When the capacity constraint and resultant airport congestion is no longer the primary concern due to serious traffic decline, the government should reconsider its slot allocation rules. Re-allocation of the available slots to serve those regional small airports could bring a “win-win” outcome for both the hub and small airports, helping airports rebound faster to mitigating the negative impact of the COVID-19 pandemic. This result also has policy relevance for other US and European hub airports, which are under the ICAO slot-coordination rules. When those international gateway airports have suffered from dramatic traffic drop, reallocating the available slots in favor of the regional services to those underserved small airports could be a feasible measure to speed up traffic recovery of both the hub and small airports.

The load factor of Airline 1 and Airline 2 can also vary with CAAC liberalizing the slots at hub Airport B. Let \( \bar{p}_1 \) and \( \bar{p}_2 \) be the load factors of Airline 1 on Market AC before and after the slot liberalization, respectively; \( \bar{p}_3 \) and \( \bar{p}_4 \) be the load factors of Airline 2 on Market AC before and after slot liberalization, respectively; \( \bar{p}_5 \) be the load factor of Airline 2 on Market AB. Then the difference of load factors of Airline 2 on Market AC is as follows,

\[
\Delta l_1 = \frac{q^*_2}{s_2} - \frac{q^*_A}{s_1} = \frac{9}{90 - 3 \beta^2} \left[ (18 - 7 \beta^2 - 2 \beta) \right] \gamma \left[ (90 - 3 \beta^2)^{-1} \right] \left[ (90 - 3 \beta^2) \alpha - 16 (9 - 4 \beta) \beta - 6 (9 - 4 \beta) \right] \gamma T
\]

where \( \gamma \) denotes the capacity of aircraft (i.e., the average number of seats per aircraft). By satisfying the nonnegativity condition of traffic at small Airport B (i.e., \( \delta < \frac{1}{2} T - \alpha \)), we have \( \Delta l_1 > 0 \).

Then for Airline 1 on Market BC, it can be obtained \( \Delta l_1 = \frac{\bar{p}_3}{\bar{s}_3} - \frac{\bar{p}_4}{\bar{s}_4} = \frac{9}{90 - 3 \beta^2} \left[ (18 - 7 \beta^2 - 2 \beta) \right] \gamma \left[ (90 - 3 \beta^2)^{-1} \right] \left[ (90 - 3 \beta^2) \alpha - 16 (9 - 4 \beta) \beta - 6 (9 - 4 \beta) \right] \gamma T = 0 \). The above results lead to Lemma 2.

**Lemma 2.** When CAAC liberalises the slots at hub Airport B to serve small Airport A, the load factor of Airline 2 would increase in Market AC (i.e., \( \bar{p}_5 > \bar{p}_3 \)), while Airline 1’s load factor in Market BC remains unchanged (i.e., \( \bar{p}_4 = \bar{p}_4 \)).

As suggested in Lemma 2, with the slot liberalization at the hub Airport B, Airline 2 would provide the interline transfer airline service in Market BC. This would increase the frequency of Airline 2 in Market AC as well. Airline 2 thus has a stronger incentive to enjoy the subsidy at the small Airport A. As a result, Airline 2 would like to reduce the load factor to further increase the flight frequency to enlarge its subsidy income. Airline 1 would have lower traffic in Market BC after the slot liberalization via Airport A. Then, Airline 1 would reduce the flight frequency in the same proportion, resulting in an unchanged load factor.

In addition, the load factor of Airline 1 and Airline 2 in the different OD markets can also vary with CAAC subsidy levels. The following comparative statics regarding CAAC subsidy \( \delta \) can be obtained for the load factors after CAAC liberalizes the slots at the hub Airport B.
\[\begin{align*}
&\frac{\partial (\tilde{q}_i^2 + \tilde{q}_s^2)}{\partial \delta} = -\frac{(54 - 25\beta^2)}{(32 \pi T)} \left( (18 - 7\beta^2 - 2\beta) \alpha - (18 - 8\beta^2) T \right) \frac{\partial \varepsilon}{\partial \delta} \\
&= \frac{\partial (\tilde{q}_i + \tilde{q}_s)}{\partial \delta} = \frac{(54 - 25\beta^2)}{32 \pi T} \left( 3 \frac{(2 - \beta)}{2} \alpha - (3 - \beta^2) T \right) \frac{\partial \varepsilon}{\partial \delta} \\
&\text{with } \alpha \geq \frac{\delta - 2\delta^2}{2T}, \text{ we have } \frac{\partial \varepsilon}{\partial \delta} < 0 \text{ and } \frac{\partial \varepsilon}{\partial \delta} = 0 \text{. The above results lead to Lemma 3.}
\end{align*}\]

Lemma 3. When the intercity travel demand is not too much damaged or has recovered to a certain level (i.e., \(\alpha \geq \frac{\delta - 2\delta^2}{2T}\)), Airline 2 tends to reduce its load factor in Market AC and Market AB with an increasing CAAC subsidy at the small Airport A, while the load factor of Airline 1 in Market BC remains unchanged.

The explanations for Lemma 3 are also intuitive. When CAAC provides a larger subsidy at the small Airport A, Airline 2 has a stronger incentive to increase the flight frequency at Airport A. This would, however, reduce the average load factor for the flights at Airport A. For Airline 1, its traffic in Market BC is reduced when Airline 2 increases frequencies for the transfer service due to higher subsidy. But Airline 1, its traffic in Market BC is reduced when Airline 2 increases frequencies for the transfer service due to higher subsidy. Thus, we have Proposition 3.

Proposition 3. When CAAC liberalizes the slots at the hub Airport B, the social welfare of the intercity travel network would overall increase. Such welfare increase is more significant with recovering market demand (i.e., a larger \(\alpha\)) and higher CAAC subsidy for the small Airport A (i.e., a larger \(\delta\)).

As shown in Proposition 3, liberalizing slots at the hub airports to serve small airports not only facilitates airport traffic recovery (see Proposition 2), but also improves social welfare. That is, society also overall benefits from such a policy when considering the overall interests of all the stakeholders. To better illustrate the above results, we also made Fig. 6. It can be seen from the figure that, after liberalizing slots at the hub airports, the difference of social welfare will increase and even gradually expand with the market recovery. In addition, with the increase of subsidies, social welfare does not monotonically increase, which proves that the amount of subsidies may have an optimal solution, which we will discuss in Section 4.

\[\begin{align*}
SW &= \left( \sum_{i=1}^{2} q_i \right) + \pi_0 + CS - \lambda \delta (f_2 + f_3) \\
\text{where } \left( \sum_{i=1}^{2} q_i \right) + \pi_0 \text{ is the sum of the profit of Airline 1, Airline 2 and HSR.}
\end{align*}\]

\[\begin{align*}
\text{CS is the passenger surplus that is already defined earlier. } \delta (f_2 + f_3) \text{ is the total amount of CAAC subsidy for airline operations at the small Airport A. } \lambda \text{ is a constant shadow price parameter of public fund spending. CAAC subsidy is sourced from the government tax income, which can also be spent in other public service areas. That is, CAAC's subsidy can be spent at a sacrifice of other projects with higher social return (i.e., the opportunity cost). Thus, } \lambda \delta (f_2 + f_3) \text{ is used to capture such a subsidy price cost of CAAC's subsidy. To simplify the model derivation for clearer insights, WLOG, the parameter } \lambda \text{ is normalized to be } 1. \text{ The equilibrium social welfare without airline service on Market AB can be calculated as follows,}
\end{align*}\]

\[\begin{align*}
\widetilde{SW} &= 4\delta (9T - 7\delta) + 9T (\alpha - 4TS) + 2\alpha (21\alpha - 105) \\
\text{(17)}
\end{align*}\]

The equilibrium social welfare with airline service on Market AB is,

\[\begin{align*}
\widetilde{SW} &= \frac{\beta^2}{\alpha} \left[ \frac{1}{6} \right] \left[ \frac{1}{T} \right] \left[ \frac{1}{\lambda} \right] \left[ \frac{1}{\delta} \right] \left[ \frac{1}{T} \right] \left[ \frac{1}{\lambda} \right] \left[ \frac{1}{\delta} \right] \\
&\text{The equilibrium social welfare increase of Market AB can be calculated as } \Delta \widetilde{SW} = \widetilde{SW} - \widetilde{SW} \text{. It can be proved that } \Delta \widetilde{SW} > 0, \text{ together with the comparative statics as } \frac{\Delta \widetilde{SW}}{\delta} > 0 \text{ (see Appendix 2 for detailed proofs). Thus, we have Proposition 3.}
\end{align*}\]

Fig. 6. The change in social welfare \(T = 1, \beta = 0.5\).

Fig. 7. The change in optimal subsidy \(T = 1, \beta = 0.5\).
4. Optimal subsidy policies

The analyses in Section 3 have been conducted conditional on the case where CAAC has already stipulated the subsidy level before the slot liberalization at the hub Airport B. As we also proposed in Section 2, CAAC may be able to adjust the subsidy level to further achieve its objective. As a government agency, CAAC needs to bear social interest to maximize social welfare (Hou et al., 2020). On the other hand, CAAC is directly responsible to improve the airline market operation and facilitate air traffic recovery, such that it would also take into consideration air traffic volume. Therefore, we propose the objective function of CAAC as a weighted sum of both social welfare and the total airline traffic, which is expressed as follows,

\[ \Lambda = \mu Q + (1 - \mu) SW \]

where \( 0 < \mu < 1 \) is the weight on the total airline traffic \( Q \) (excluding the HSR traffic) and the social welfare \( SW \). Thus, CAAC could also adjust its subsidy level for the small Airport A in order to maximize its objective function value. The optimal CAAC subsidy \( \delta^a \) and \( \tilde{\delta}^a \) can be solved for the case with and without slot liberalization at the hub Airport B, respectively,

\[ \delta^a = \frac{(28\alpha - 277)/110}{(1 - \mu)} + \frac{115}{(1 - \mu)} \]

\[ \tilde{\delta}^a = \frac{18\beta(266a - 195T - 582) - \beta'(1288a - 801T - 1725)}{1207\mu - 6084\mu^2 + 4860} \]

where \( \alpha = \alpha(1 - \beta) + \beta\delta \) and \( \beta' = 575\beta^2 + 3492\beta + 4860 \).

We can obtain the comparative statics of \( \delta^a \) and \( \tilde{\delta}^a \) with respect to total airline traffic weight \( \mu \), which yields the following results and Lemma 4,

\[ \frac{\partial \delta^a}{\partial \mu} = \frac{-\mu + 21}{22(1 - \mu)^2} > 0 \]

\[ \frac{\partial \tilde{\delta}^a}{\partial \mu} = \frac{-\mu + 3(575\beta^2 + 3492\beta + 4860)}{2(1207\mu - 6084\mu^2 + 4860)(1 - \mu)^2} > 0 \]

Lemma 4. Regardless of the slot liberalization at the hub Airport B or not, the optimal subsidy at the small Airport A increases with CAAC’s emphasis on the total airline traffic (i.e., the air traffic recovery).

Lemma 4 can be better illustrated by using Fig. 7, which can directly explain that the optimal subsidy will increase with the emphasis of CAAC to the total airline traffic, and when \( \mu \) is close to 1, the optimal subsidy will be infinite, but it is impossible in reality. It suggests that an increasing subsidy at the small Airport B is conducive to improving total airline traffic. It can also be proved that \( \frac{\partial \delta^a(\tilde{\delta}^a)}{\partial \mu} = \frac{3(1168\beta^2 - 594\alpha\beta + 540)}{11(1207\mu - 6084\mu^2 + 4860)(1 - \mu)^2} > 0 \), such that a higher subsidy is more effective to increase the total airline traffic when the slots are liberalized at the hub Airport B.

The comparisons of the optimal subsidy levels \( \delta^a \) and \( \tilde{\delta}^a \) can be found in Appendix 2. In addition, the equilibrium air traffic and social welfare can also be obtained and benchmarked under the optimal subsidy level, with and without liberalizing slots at the hub Airport B. These results lead to Proposition 4, with its proof collated in Appendix 2 as well.

Proposition 4. Liberalizing slots at hub Airport B to serve small Airport A would lead to a higher optimal subsidy level for the small Airport A and higher total airline traffic (i.e., \( \tilde{\delta}^a > \delta^a; \tilde{Q} > Q^a \)). Social welfare is more likely to be improved when the potential market is sufficiently large.

As suggested by Proposition 4, CAAC needs to provide a higher subsidy to small Airport A after liberalizing the slots at the hub Airport B. This is because the entry of Airline 2 in Market AB would generate new airline traffic in the network and also intensifies the airline competition in Market BC. Thus, the marginal increase in the total airline traffic of the subsidy at the small Airport A could be higher with slot liberalization at the hub Airport B (suggested by Lemma 4 as well). When CAAC accounts for airline traffic recovery in its objective, it would like to offer a larger subsidy together with the slot liberalization at the hub Airport B. The equilibrium total airline traffic would also increase as a result. However, social welfare is not necessarily improved under the optimal subsidy after liberalizing slots at the hub Airport B. This is because when CAAC cares about airline traffic recovery, it tends to provide a higher subsidy to encourage airline traffic. Such a high subsidy could be at the cost of public money spending, which would instead damage social welfare. This is more likely to occur when the intercity travel market has not been well recovered (i.e., a small \( \alpha \)), such that the subsidy needs to be high to boost the airline traffic. Therefore, we conclude that, when CAAC is able to adjust its subsidy level to maximize its objective function value (i.e., a weighted sum of both total airline traffic and social welfare), social welfare can be damaged. This thus calls for caution in policymaking. When COVID-19 has seriously reduced the intercity travel market demand, CAAC might speed up airline traffic recovery at a sacrifice of social welfare when it also liberalizes the slots at the hub Airport B. Once the intercity travel demand rebounds with better pandemic control, social welfare could also improve with CAAC’s subsidy adjustment.

5. Conclusion

The COVID-19 pandemic has badly hit the airline industry, in particular the international air travel demands. Many gateway and hub airports now have ideal slots available for reallocation. Airport traffic recovery has become the primary challenge for the major airports to survive the crisis. As most gateway and hub airports in China and around the world are originally subject to slot-coordination due to capacity constraints, the services to small and regional airports have been largely restricted. With pandemic well controlled domestically, the Chinese government recently liberalized the hub airport slots to allow services with small airports. This policy mainly aims to speed up airline traffic recovery. This study thus analytically examines the effect of this policy on airline traffic recovery and other market equilibrium outcomes. In addition, the government subsidy to the small airports has also been considered together with such a slot liberalization policy. We found that the slot liberalization can speed up airport traffic recovery for both hub and small airports. The hub airport slot liberalization leads to a lower level of minimum subsidy to sustain the survival of the small airports. Given any fixed level of subsidy to the small airport, both the total airport traffic and social welfare would improve with the slot liberalization at the hub airport. When the government can adjust the level of subsidy after liberalizing the hub airport slots, the subsidy could be excessive, if the government emphasizes too much on airport traffic recovery. This would, however, harm the overall social welfare. Our findings also offer useful policy implications to other markets such as the US and Europe, where a large number of slots are now available for reallocation. Allocating these slots to the small airports in nearby regions with lower imported case risk of COVID-19 would be feasible and can benefit both hub and small airports in terms of fast traffic recovery.

This study is also subject to some limitations while opening avenues for future studies. First, to derive clearer economic insights, we propose a simplified intercity network consisting of only one small airport. In reality, one hub airport can have multiple candidate small airports to serve, it thus could be more complex to rationalize the optimal slot...
allocations with multiple regional airports. Second, our model does not explicitly consider how the liberalized slots are allocated to individual airlines. To avoid potential slot hoarding behaviors due to existing grandfather practice (Sheng et al., 2019), it is suggested for CAAC to regulate the allocated hub airport slots to be exclusively used to serve the small airports. These slots should be returned to airports for the original international flights once the pandemic has been well controlled globally and the international air travel demand resumes. Moreover, when several airlines desire the available slots to serve the small airports, CAAC also needs to come up with a clear selection criterion or mechanism, for example, a slot auction or bidding as suggested in Sheng et al. (2015). Through such auction, CAAC might be able to choose the most efficient and capable airlines, probably requiring lower subsidy and providing the lower ticket price. But the explicit modeling of the slot allocation with multiple regional airports, CAAC also needs to come up with a clear selection criterion or mechanism.

Aside from the modeling, there are also some meaningful extensions for future research, which, however, are apparently out of the scope of the current study. These are all meaningful extensions but are apparently out of the scope of the current study. Last, our caution would greatly complicate the model, while not necessarily being unnecessary or critical. Therefore, it is worth noting that the theoretical findings can be empirically verified later with more airport and airline data that can be collected with a reasonably long-time frame. These are all meaningful extensions but are apparently out of the scope of the current study. Last, our caution would greatly complicate the model, while not necessarily being unnecessary or critical. Therefore, it is worth noting that the theoretical findings can be empirically verified later with more airport and airline data that can be collected with a reasonably long-time frame.

## Appendix 1

### Table A1

The passenger throughput for large Chinese airports amid the COVID-19 pandemic (from Jan–Aug 2020)

| 2019 ranking | Airport | Code | Jan–Aug 2020 ranking | Change in ranking | Passenger throughput from Jan–Aug 2020 (million) | Change (%) |
|--------------|---------|------|----------------------|-------------------|-----------------------------------------------|------------|
| 1            | Beijing Capital | PEK 7 | -6                   | 18.33             | -72.7                                        |
| 2            | Shanghai Pudong | PVG 6 | -4                   | 18.43             | -64.2                                        |
| 3            | Guangzhou      | CAN 2 | 1                    | 24.32             | -49.8                                        |
| 4            | Chengdu        | CTU 1 | 3                    | 24.32             | -34.7                                        |
| 5            | Shenzhen       | SZX 3 | 2                    | 21.96             | -37.3                                        |
| 6            | Kunming        | KMG 5 | 1                    | 18.97             | -41.8                                        |
| 7            | Xi’an          | XIF 8 | -1                   | 18.24             | -42.3                                        |
| 8            | Shanghai Hongqiao | SHA 9 | -1                   | 17.41             | -42.2                                        |
| 9            | Chongqing      | CGK 4 | 5                    | 20.37             | -32                                           |
| 10           | Hangzhou       | HGH 10 | 0                   | 15.87             | -40.8                                        |
| 11           | Nanjing        | NKG 12 | -1                  | 11.24             | -45.4                                        |
| 12           | Zhengzhou      | CGQ 11 | 1                   | 12.44             | -36.7                                        |
| 13           | Xiamen         | XMN 15 | -2                  | 9.40              | -49.1                                        |
| 14           | Wuhan          | WUH 26 | -12                 | 5.64              | -69                                           |
| 15           | Changsha       | CSX 13 | 2                   | 10.76             | -40.6                                        |
| 16           | Qingdao        | TAO 17 | -1                  | 8.91              | -47.9                                        |
| 17           | Haikou         | HAK 16 | 1                   | 9.10              | -44.6                                        |
| 18           | Urumqi         | URC 23 | -5                  | 6.36              | -60                                           |
| 19           | Tianjin        | TSN 19 | 0                   | 7.75              | -53.1                                        |
| 20           | Guiyang        | KWE 14 | 6                   | 9.60              | -34.3                                        |
| 21           | Harbin         | HRB 21 | 0                   | 6.98              | -50.2                                        |
| 22           | Shenyang       | SHE 20 | 2                   | 7.07              | -48.9                                        |
| 23           | Sanya          | SYX 18 | 5                   | 8.41              | -37.7                                        |
| 24           | Dalian         | DLC 36 | -12                 | 4.46              | -67.2                                        |
| 25           | Jinan          | TNA 22 | 3                   | 6.86              | -42.3                                        |
| 26           | Nanning        | NNG 25 | 1                   | 5.94              | -44.5                                        |
| 27           | Lanzhou        | LHW 24 | 3                   | 6.08              | -41.4                                        |
| 28           | Fuzhou         | FOC 30 | -2                  | 5.05              | -49.7                                        |
| 29           | Taiyuan        | TYN 32 | -3                  | 4.94              | -48.2                                        |
| 30           | Changchun      | CGQ 31 | -1                  | 4.95              | -46.1                                        |
| 31           | Nanchang       | KHN 27 | 4                   | 5.38              | -41.5                                        |
| 32           | Huludong       | HET 34 | -2                  | 4.64              | -48.5                                        |
| 33           | Ningbo         | NGB 29 | 4                   | 5.06              | -39.8                                        |
| 34           | Wenzhou        | WNZ 28 | 6                   | 5.11              | -38.9                                        |
| 35           | Zhuhai         | ZHU 37 | -2                  | 3.85              | -53.3                                        |
| 36           | Hefei          | HFE 33 | 3                   | 4.92              | -40.9                                        |
| 37           | Shijiazhuang   | SJW 35 | 2                   | 4.59              | -42.7                                        |
| 38           | Yinchuan       | INC 38 | 0                   | 3.75              | -47.2                                        |
| 39           | Yantai         | YNT 39 | 0                   | 3.19              | -51.3                                        |

**Notes.**
1. The airports listed are those with a passenger throughput of more than 10 million in 2019.
2. The 2019 ranking is based on the annual passenger throughput in 2019.
3. Source: Compiled by the authors with raw data from the website: www.carnoc.com.

### Author’s statement

**Meng Hou:** Methodology, Investigation, Formal analysis, Validation. **Kun Wang:** Conceptualization, Formal analysis, Investigation, Writing–original draft. **Hangjun Yang:** Conceptualization, Formal analysis, Writing - review & editing, Supervision. All the co-authors declare that we do not have any copyright issue with this paper. The paper has not been submitted or published in other journals. We also do not see any conflict of interest involved in this submission. All the related financial support from related research funds have been appropriate acknowledged.

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Appendix 2

Proof of Proposition 1

We first compare Airline 2’s equilibrium profits with and without entry into Market AB (i.e., \( \Delta \pi_2 = \pi_2^e - \pi_2^w \)),

\[
\Delta \pi_2 = \frac{\partial \pi}{\partial e} \left( \begin{array}{l}
\beta \left[ (2099\alpha(\alpha + 75 - 12)T + 3483\beta) + 690[1816T - 1225\alpha - 1127\beta] - 187(155T - 626\beta) - 10208\beta \right] \\
-392\alpha^2(127T - 6\alpha - 76) + 1764\alpha\beta(15T - 46\alpha - 286) \\
-5292\alpha(30T - 29\beta) + 162(141T - 376\beta)(141 - 208\beta) \\
\end{array} \right) \\
\frac{49(54 - 25\beta)}{(54 - 25\beta)^2}
\]

(A1)

We get the derivative of \( \Delta \pi_2 \) with respect to \( e \),

\[
\frac{\partial \pi}{\partial e} = \frac{\{ [112\beta + 231\beta - 414\alpha] + (135 - 24\beta)T + 146(\beta^2 - 18) \} \} \\
\frac{\{ [(54 + 25\beta) - 84\beta]\alpha + 6\beta(3T - 8\beta) \}}{(54 - 25\beta)^2}
\]

(A2)

With \( 0 < \beta < 1 \) and \( \delta \geq \{ \hat{\delta}, \hat{\delta}' \}_\text{max} = \frac{2}{3}T - \alpha \), we have \( 54 - 25\beta^2 > 0 \) and \( \{ (12\beta^2 + 231\beta - 414\alpha) + (135 - 24\beta^2)T + 146(\beta^2 - 18) \} < 0 \), then we have \( \beta^* = \frac{\{ 246 - 97 + 42\alpha - 3 \} \{ 46\alpha^2 + (4T - 224)\beta + 9(T - 2\beta)^2 \} \}}{25(54 - 25\beta)^2} \). If \( \beta > \beta^* \), we get \( \frac{\partial \Delta \pi_2}{\partial e} < 0 \) if \( \beta \leq \beta^* \), \( \frac{\partial \Delta \pi_2}{\partial e} \geq 0 \), and when \( \beta = \beta^* \) we have \( (\Delta \pi_2)_{\min} \geq 0 \), so the \( \Delta \pi_2 \) is always greater than 0.

Q.E.D.

Proof of Proposition 2

With slot liberalization at the hub Airport B, the two airports’ traffic volumes are,

\[
\hat{Q}_s = \hat{Q}_s^e = \frac{2\alpha(12 - \beta) - 4\beta(\delta + 2\alpha) - 3T + 12\delta}{33 - 12\beta^2}
\]

(A3)

After slot liberalization, the two airports’ traffic volumes are,

\[
\hat{Q}_s' = \hat{Q}_s' + \hat{Q}_r' = \frac{(84T + 92\alpha + 74\delta)\beta^2 + 96\alpha\beta + 216T - 360\alpha + 252\beta}{162 - 75\beta^2}
\]

\[
\hat{Q}_s'' = \hat{Q}_s'' + \hat{Q}_r'' = \frac{(24T + 62\alpha - 146\beta)^2 - 81ab - 81T + 270\alpha + 108\delta}{162 - 75\beta^2}
\]

(A4)

Then we get the differences in the two airports’ traffic with and without slot liberalization at the hub Airport B,

\[
\Delta \hat{Q}_s = \hat{Q}_s' - \hat{Q}_s = \frac{14(42 - 7\beta^2 - 16\alpha)\alpha + 4(222 - 53\beta^2)\delta - 9(50 - 19\beta^2)T}{378 - 175\beta^2}
\]

\[
\Delta \hat{Q}_s = \hat{Q}_s'' - \hat{Q}_s = \frac{7(54 - 4\beta^2 - 27\beta)\alpha + 4(81 - 7\beta^2)\delta - 3(135 - 52\beta^2)T}{378 - 175\beta^2}
\]

(A5)

And with \( 0 < \beta < 1 \), we have \( \Delta \hat{Q}_s > 0 \). \( \Delta \hat{Q}_s > 0 \).

Q.E.D.

Proof of Proposition 3

In order to simplify the derivations, WLOG, it is first assumed \( \beta = \frac{1}{2} \) (i.e., the moderate substitutability between air and HSR services on Market AB).

Then we obtain the difference of social welfare with and without airline service in Market AB (i.e., \( \Delta SW = SW - SW' \),

\[
\Delta SW = \frac{7(54 - 4\beta^2 - 27\beta)\alpha + 4(81 - 7\beta^2)\delta - 3(135 - 52\beta^2)T}{378 - 175\beta^2}
\]

(A5)
\[ \Delta \hat{SW} = \frac{72\alpha(342384\alpha - 372486 - 1632557) + 9\alpha(531169\alpha - 3460492\alpha) + 16696064\alpha^2}{3217624} \]  
(A6)

We consider this social welfare difference as a function of \( \delta \), i.e., \( \Delta \hat{SW}(\delta) \) and this is a concave function. With \( \delta \hat{SW}(\delta) = 0 \), the left and right roots can be obtained,

\[ \delta_1 = \frac{-1337\sqrt{96\alpha(796\alpha - 9243T) + 1840417^2} + 1027152\alpha - 489765T}{223488} \]  
(A7)

\[ \delta_2 = \frac{1337\sqrt{96\alpha(796\alpha - 9243T) + 1840417^2} + 1027152\alpha - 489765T}{223488} \]

With \( \frac{1}{2}T - \alpha \leq \delta \leq 3T + \frac{1}{2}\alpha \), we have \( \delta_1 < 3T < \delta < \delta_2 \), then we can get \( \Delta \hat{SW} > 0 \).

With \( \alpha > \frac{1092624 - 800739\alpha}{1092624} \), we get the first derivative function of \( \Delta \hat{SW} \) with respect to \( \delta \),

\[ \frac{\partial \Delta \hat{SW}}{\partial \delta} = \frac{293240\alpha - 218524\alpha - 160146T}{328329} > 0 \]  
(A8)

The first derivative function of \( \Delta \hat{SW} \) with respect to \( \alpha \) is,

\[ \frac{\partial \Delta \hat{SW}}{\partial \alpha} = \frac{293240\alpha + 143516\alpha - 223992T}{328329} > 0 \]  
(A9)

Then we also examine the social welfare differences with alternative values of \( \beta (\beta = \frac{1}{3}, \beta = \frac{1}{2}, \beta = \frac{2}{3} \) and \( \beta = \frac{3}{2} \)), the conclusions are qualitatively consistent.

Q.E.D.

**Proof of Proposition 4**

In order to simplify the derivations, WLOG, it is first assumed \( \beta = \frac{1}{2} \) (i.e., the moderate substitutability between air and HSR services on Market AB). Then, we subtract \( \hat{\delta}^a \) from \( \hat{\delta}^\alpha \) and obtain,

\[ \Delta \hat{\delta} = \hat{\delta}^\alpha - \hat{\delta}^a = 9(162721\alpha - 363024\alpha)(1 - \mu) + 2442150\alpha \]  
\[ \text{3004705}(1 - \mu) \]  
(A10)

Taking the first derivative of \( \Delta \hat{\delta} \) with respect to total airline traffic weight \( \mu \) yields \( \frac{\partial \Delta \hat{\delta}}{\partial \mu} = \frac{9(162721\alpha - 363024\alpha)(1 - \mu) + 2442150\alpha}{3004705(1 - \mu)} > 0 \), and \( \Delta \hat{\delta}_{\min} = \frac{9(162721\alpha - 363024\alpha)(1 - \mu) + 2442150\alpha}{3004705(1 - \mu)} > 0 \), then we have \( \hat{\delta}^a > \hat{\delta}^\alpha \).

Substituting \( \hat{\delta}^\alpha \) and \( \hat{\delta}^a \) into \( \hat{Q}^\alpha \) and \( \hat{Q}^a \), respectively, where \( \hat{Q}^\alpha = \tilde{q}_1^\alpha + \tilde{q}_2^\alpha + \tilde{q}_3^\alpha + \tilde{q}_4^\alpha \) and \( \hat{Q}^a = \tilde{q}_1^a + \tilde{q}_2^a + \tilde{q}_4^a \) we have,

\[ \hat{Q}' = \frac{2(8\alpha - 3T)(1 - \mu) + 5\mu}{11(1 - \mu)} \]  
(A11)

\[ \hat{Q}^a = \frac{3(8\alpha - 3T)(1 - \mu) + 5\mu}{11(1 - \mu)} \]

Subtracting \( \hat{Q}^a \) from \( \hat{Q}' \),

\[ \Delta \hat{Q} = \frac{143865\alpha - 60555\alpha + 97610\mu}{600941(1 - \mu)} > 0 \]  
(A12a)

Then we get \( \hat{Q}' > \hat{Q}^a \).

Similarly, for the change in social welfare, substituting \( \hat{\delta}^\alpha \) and \( \hat{\delta}^a \) into \( \hat{SW}^\alpha \) and \( \hat{SW}^a \), respectively, we have,

\[ \hat{SW}^\alpha = \frac{\mu^2(0.24274\alpha^2 - 146056\alpha T + 489417^2 - 113569^2)}{109262(1 - \mu)} \]  
(A12b)

\[ \hat{SW} = \frac{\mu^2(1666\alpha^2 - 252\alpha T + 126T^2 - 225)}{990(1 - \mu)} \]

substituting \( \hat{SW}^\alpha \) from \( \hat{SW}^\alpha \), we obtain,

\[ \hat{SW} = \frac{\mu^2(5960038\alpha^2 - 86064732\alpha T + 16896789\alpha^2 - 43924680)}{5408460(1 - \mu)} \]  
(A13)
Taking the first derivative of $\Delta SW$ with respect to total airline traffic weight $\alpha$ yields 
\[
\frac{\Delta SW}{\Delta \alpha} = \frac{3\cdot15\mu^2(4848014435328 + 1564313723687777)}{29800192(1 - \mu)T}^{1/2} + \frac{2346470585305(1 - 2\mu)T^2}{29800192(1 - \mu)T} \]

When $\alpha \geq \alpha'$, $\Delta SW \geq 0$, and $\Delta SW < 0$ with $\alpha < \alpha'$. Then we also examine the outcomes with alternative values of $\beta$ (i.e., $\beta = \frac{3}{4}, \beta = \frac{4}{5}, \beta = \frac{8}{9}$ and $\beta = \frac{9}{10}$), and the conclusions are qualitatively consistent.

Q.E.D.

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