Hindawi
Mathematical Problems in Engineering
Volume 2022, Article ID 8372764, 17 pages
https://doi.org/10.1155/2022/8372764

Research Article

Optimal Contract for Reducing Flight Delays in EU: In the Context of SESAR

Estelle Malavolti[1] and Chunan Wang[2,3,4]

[1]*French Civil Aviation University (ENAC) and Toulouse School of Economics, Toulouse, France*
[2]*School of Economics and Management, Beihang University, Beijing, China*
[3]*Beihang Hangzhou Innovation Institute Yuhang, Hangzhou, China*
[4]*MoE Key Laboratory of Complex System Analysis and Management Decision, Beijing, China*

Correspondence should be addressed to Chunan Wang; chnwang@buaa.edu.cn

Received 5 August 2021; Accepted 5 January 2022; Published 3 February 2022

Academic Editor: Adnan Maqsood

In the context of the SESAR (Single European Sky Air traffic management Research) Joint Undertaking, the role that the air navigation service provider (ANSP) could play has been reconsidered. ANSP manages traffic and deals with potential conflict situations and external events, which have led to the reorganization of the air traffic. The modification of traffic inevitably leads to delays for airlines, which is costly. In this study, we suggest that ANSP could provide a costly delay reduction service to airlines. Indeed, if ANSP has several solutions for traffic conflict resolution or reorganization, there is room for a choice between these solutions using additional criteria. Our study thus proposes an original model in which we determine the optimal design of a delay reduction contract signed between welfare- or profit-maximizing ANSPs and a monopoly airline. We give some comparative statics, in particular, the evaluation of the impact of a modification in safety standards on the contract.

1. Introduction

Aviation in Europe is expected to experience rapid growth and more delays in the future. According to STATFOR [1], in the most likely scenario, there will be 14.4 million flights in Europe in 2035; 50% more than in 2012. Moreover, air traffic growth will be limited by the available airport capacity. When the capacity limits are reached, congestion at airports will rapidly increase, leading to even more delays. In addition, in Europe, 15% of the flights are currently delayed due to ATM (Air Traffic management) reasons. To improve and meet the development of the EU air transport sector, in 2004, the European Union and EUROCONTROL founded the SESAR (Single European Sky Air traffic management Research) Joint Undertaking, in which meeting future safety needs and reducing delays are important targets (see [2]; European [3], 2015; [4]). In the context of SESAR, various propositions to reduce delays have been made, such as increasing the quality of air transport services. These propositions are mainly technical; however, a delay reduction service has also been considered. This service corresponds to an evolution in the role of the air navigation service provider (ANSP), which was initially established to be in charge of air traffic management. Under the delay reduction service, when facing potential delays, an airline will contact ANSP to find a solution to limit or to reduce delays well in advance. After receiving an airline's request, ANSP will determine several solutions that satisfy all regulation constraints. Then, by costly calculation, evaluation, and coordination, ANSP will select the solution to most effectively reduce delays in line with airlines' demands and then implement it. In the short term, the service can be provided free of charge due to the generous funding of SESAR. In the long term, however, ANSP will face financial constraints. Thus, a contract (hereafter, a "delay reduction contract") should be signed between ANSP and the airlines, in order to make the service sustainable. This study aims to study the optimal design of the delay reduction contract (in the USA, the Next Generation Air Transportation System is the counterpart of the SESAR program. This program also focuses on the improvement of the performance of ATM. As such, our results can be easily considered).

A delay reduction contract will be set between ANSP and a monopoly airline. This will consist of a degree of reduction in delays to be incurred as a result of the conflict situation to which ANSP commits with a transfer payment made by the airline. We assume that the incentives and motivations of the airline to sign such a contract are unknown by ANSP. This assumption allows us to consider the fact that airlines may vary in their willingness to pay for the same degree of reduction. Indeed, some airlines may greatly value being on time or experiencing as little delay as possible. Incentives from the demand side (reputation and quality of service) and the supply side (network effect and cost of fuel) may explain why airlines particularly value as little delay as possible. We consider that this information is private and that the design of the optimal contract is an adverse selection problem, which results in the well-known trade-off between efficiency and rent extraction.

We analytically derive optimal contracts, considering both the welfare- and profit-maximizing ANSPs. Indeed, we consider that a certain part of the cost of choosing which solution to adopt when delays are to occur has to be taken either by the society (welfare maximization) or by a private firm (profit maximization, only for the delay reduction service). Our results are consistent with the principal-agent literature: under incomplete information, the high-type airline (i.e., a high value of delay reduction) receives an information rent in order to avoid them taking the contract designed for the low-type airline. More interestingly, when the passenger surplus is taken into account, the airline can even be subsidized to participate in the delay reduction service in order to achieve higher welfare.

Furthermore, we conduct comparative static analysis to study the effect of the relevant exogenous parameters on optimal contracts, such as safety standards and flight frequency. This analysis allows us to understand how the delay reduction benefits and the cost of producing the delay reduction service interact. Finally, we use numerical examples to study when a welfare-maximizing ANSP has to use public funds to provide the delay reduction service. The trade-off will be dependent on the impact of the delay reduction on the passenger surplus. Indeed, if passengers greatly value the delay reduction, then it becomes welfare improving to foster the service of delay reduction.

1.1. Related Literature. Our study contributes to the literature on air traffic management in two principal ways. The ATM literature centered on delays mainly focuses on the reduction in global delays in the air transport system. The proposed changes primarily consist of improving the methods, which solve conflicts (new algorithms and speed of computation) or allocate the slots for takeoff and landing (see [5]), and can be found in the operational research literature. However, global efficiency is sought, and several solutions may lead to the same result in terms of global delays. We propose to complete this analysis by allowing for the possibility of selecting particular solutions among those available, in which some airlines could choose the maximum amount by which they will be delayed. Then, we also model the ANSP as a strategic agent and propose to assess the performance of the ATM system while introducing the opportunity to propose a delay reduction service. From this perspective, our study is related to Blondiau et al. [6], in which the relationship between the ANSP and the regulator is modeled. Instead, we consider that ANSP has no personal agenda and faces asymmetric information regarding the airlines. The performance of the ANSP in controlling air traffic has been assessed several times. Economists generally focus on the benchmarking of cost efficiency, as in Bilotkach et al. [7] with EUROCONTROL data from 2002 to 2011, or with the study by Button and Neiva [8], which focuses on the reform of the functional airspace blocks. The performance is, however, measured ex-post, and no economic model explaining where gains or losses can be found is supported by these studies. We propose a simple model to formalize the interaction between ANSP and an airline, thus contributing to formalize how performance could be achieved when making use of the relationship between the stakeholders.

Our second main contribution to the ATM literature concerns the way delays are modeled. Among others, Brueckner [9, 10] models the delay cost as a nondecreasing function of flight frequency during the peak travel period of a day. Brueckner and Van Dender [11] collapse the peak and off-peak travel periods into a single travel period, in which delays always exist. The US Federal Aviation Administration [12] models delays as a convex function of flight frequency and airport capacity. This delay function is estimated from the steady-state queuing theory and has been used by Morrison [13], Zhang and Zhang [14–16], and Basso [17]. Pels and Verhoef [18]; De Borger and Van Dender [19]; Basso and Zhang [20]; Yang and Zhang [21, 22]; and Gillen and Mantin [23] use a linear delay function of flight frequency. In this study, we model the delay function in order to capture the causes of delays. In particular, our delay function consists of the delays due to exceptional events (exceptional events can be, for example, adverse weather conditions, aircraft defects, and airport facility limitations) and the delays induced by other flights, in which the number of exceptional events in a slot follows a Poisson distribution. These assumptions follow the typology of Cook and Tanner [24]. In their study, the cost of the delays of airlines is calculated by strategic delays (those accounted for in advance) and tactical delays (those incurred on the day of operations and not accounted for in advance). Strategic delays are for "adding buffer" to the airline schedule. Tactical delays include "primary" delays, and "secondary" or "reactionary" delays, in which original delays caused by one aircraft ("primary" delays) cause "knock-on" effects to the rest of the network (known as "secondary" or "reactionary" delays). The delays in our model mainly correspond to tactical delays, as in Cook and Tanner [24]. Moreover, the delays due to exceptional events in own slots and the delays induced by other flights in the delay function of this model roughly correspond to primary and reactionary delays, as defined by Cook and Tanner [24], respectively.

Because there is an asymmetric information situation between ANSP and the airline, we need to use incomplete information contract theory. In the incentive theory and regulation literature, Caillaud et al. [25] summarize two types of the regulator's objective function, that is, distributional objectives and the cost of public funds. Baron and Myerson [26] and Baron and Besanko [27] use the objective function distributional objectives, while Laffont and Tirole [28] use the objective function with the cost of public funds. This study considers the cost of public funds when ANSP acts as a social planner. In particular, because passengers may benefit from the service but do not pay ANSP, it is possible that the service is socially desirable, while the airline's benefit from the service is not as high as the total cost of providing the service. In this case, ANSP has to use public funds to subsidize the service and thus considers the cost of public funds in the objective function.

The rest of the study is organized as follows. Section 2 introduces the model. Section 3 derives optimal delay reduction contracts. Section 4 studies the adjustment of optimal contracts with respect to the modification of the main exogenous parameters, such as safety (a priority of the ATM) and frequency (a measure of the intensity of the activity consequently producing delays). Section 5 uses numerical examples to study when a welfare-maximizing ANSP has to use public funds to provide the delay reduction service. Section 6 concludes the study.

2. The Model

We consider a monopoly ANSP, a monopoly airline, passengers with a mass N, and an air transport system connecting two airports. Indeed, our main objective is to determine under which conditions an airline may want to sign a contract with ANSP, which results in shorter delays, and if so, what form the contract should take.

Conditional on the use of the airline, following Brueckner [29]; Brueckner and Flores-Fillol [30]; and Flores-Fillol [31, 32], the passenger utility is as follows:

$$v = y - p + b + a(s) - \alpha\ D(s). \qquad (1)$$

In equation (1), y is the passengers' income; p is the fare; b is the passengers' travel benefit, which is uniformly distributed on the support $[\underline{b}, \overline{b}]$; $a(s)$ is the passengers' utility gain from a safety standard s with $a\prime(s) \geq 0$; α is the passengers' value of time; and $D(s)$, which is a function of safety standard s, is the expected delays per flight (in time units).

With respect to the passenger utility function, there are several points to be noted. First, there is another type of passenger utility function, that is, a quadratic passenger utility, proposed by Dixit [33]. Such utility function can be found in Richard [34]; Fu et al. [35]; Lin [36, 37]; Jiang and Zhang [38]; D'Alfonso et al. [39]; and Wang and Wang [40, 41]. The main purpose of this type of utility function is to include two substitutable air transport services, reflecting horizontal product differentiation. As there is only one type of air transport service in this model, a linear passenger utility function is enough to satisfy the research purpose and helps to simplify the analysis. Second, according to the University of Westminster [42], three types of passenger costs of delay may be considered: (i) "hard" costs (borne by the airline, such as rebooking and compensation); (ii) "soft" costs (borne by the airline, such as the loss of market share due to passenger dissatisfaction); and (iii) "internalized" costs (borne by the passenger and not passed on to the airline, such as the potential loss of business due to the late arrival at meetings). The passengers' value of time in this model mainly refers to the "internalized" costs in the University of Westminster [42]. Third, a safety standard is introduced to the model in order to take into account the fact that the premier objective of ATM is to ensure a safe flight, no matter the delays induced. Our analysis helps to understand the choices that could be made among the several regulations when conflict occurs, which satisfy the safety standards. This choice could be driven by the fact that some airlines want to buy the delay reduction service. Moreover, the safety standard s is exogenous and can vary within $[\underline{s}, \overline{s}]$.

The specification we build of expected delays per flight is as follows:

$$D(s) = 2\left[\sum_{k=0}^{+\infty} \frac{(\beta T/f)^k e^{-(\beta T/f)}}{k!} k g(s) + \gamma\beta\left(\frac{T}{f}\right)^{-1} g(s)\right]. \qquad (2)$$

In equation (2), the first term in the square brackets is the delays due to exceptional events in own slot. We assume that the number of exceptional events in a slot follows a Poisson distribution with parameter $\beta T/f$, in which β is the exceptional event arriving rate; T is the number of available hours; and f is the flight frequency. It is assumed that flights are evenly spaced during available hours. Consequently, the duration of a slot is T/f. k is the number of exceptional events, $g(s)$ is the number of delays caused by an exceptional event, and $g'(s) \geq 0$ captures the fact that the higher the safety standard, the longer delays will be (see [2, 4, 43]). The second term in the square brackets is the delays induced by other flights, which decreases with T/f and increases with β and $g(s)$. What is more, the parameter $\gamma > 0$ is the so-called "delay externality parameter" in this study. A greater γ implies a more severe effect from other flights. In fact, the second term can be interpreted as the delays caused by airport congestion. The square brackets are two times because we consider two airports.

Passengers also have an outside option, for instance, to travel by train. Conditional on the use of the outside option, the passenger utility is $v_0 = y + z$, in which z is the net benefit of the outside option.

Hence, a passenger chooses to travel by plane when $y - p + b + a(s) - \alpha\ D(s) \geq y + z$, which is equivalent to $b \geq p - a(s) + \alpha\ D(s) + z$, that is, when the travel benefit exceeds the ticket price minus the passengers utility from safety, plus the impact of delays, parametrized by the safety standard, plus the value of the outside option. The air traffic (air passengers' demand) then equals the following:

$$q = \int_{p-a(s)+\alpha D(s)+z}^{\bar{b}} \frac{N}{\bar{b}-\underline{b}} db = [\bar{b} - p + a(s) - \alpha D(s) - z] \frac{N}{\bar{b}-\underline{b}}. \quad (3)$$

We assume a separable airline cost function, composed of the costs to operate traffic, to launch an activity (and thus this part is fixed), and the cost of being delayed. We assume also that airlines may differ with respect to their value of time (we will further consider only one airline, which can be of the high value of time type or low value of time type. Obviously, the extensions would consider competition between airlines and how it influences the delay reduction contract). Hence, the airline's cost is as follows:

$$c_{\text{airline}} = \tau q + \delta f + \theta f D(s). \quad (4)$$

In equation (4), τq is the variable cost, in which τ is the marginal cost per seat; δf is the fixed cost, in which f stands for the frequency of flights, that is, a given number of flights per unit of time; δ is the fixed operating cost of a flight; and $\theta f D(s)$ is the supply-side delay cost, in which θ is the airline's value of time. θ may not be observed by ANSP. However, it is common knowledge that θ belongs to the set $\Theta = \{\bar{\theta}, \underline{\theta}\}$, in which $\bar{\theta}, \underline{\theta} > 0$ and $\Delta\theta = \bar{\theta} - \underline{\theta} > 0$. If θ is the airline's private knowledge, the airline can be the one with $\bar{\theta}$ or $\underline{\theta}$ with probabilities μ and $1-\mu$, respectively. These probabilities represent ANSP prior to the type of airline (low value of time type or high value of time type).

The airline maximizes profit by choosing the fare (in this model, flight frequency is not an endogenous decision variable of the airline. One reason can be the slot control in Europe. That is, at all major European airports, takeoff and landing slots are allocated through "grandfather rights" and the "use it or lose it" rule. However, in the comparative static analysis, we will study how the change in flight frequency affects optimal contracts), that is,

$$\max_{\{p\}} \pi = pq(p) - [\tau q(p) + \delta f + \theta f D(s)]. \quad (5)$$

Letting $\eta \equiv N/(\bar{b} - \underline{b})$, the optimal solution of equation (5) is as follows:

$$\begin{aligned} p^*(s) &= \frac{1}{2}[\bar{b} + \tau + a(s) - z - \alpha D(s)], \\ q^*(s) &= \frac{1}{2}\eta[\bar{b} - \tau + a(s) - z - \alpha D(s)], \\ \pi^*(\theta, s) &= \underbrace{-\frac{1}{4}\eta\{2[\bar{b} - \tau + a(s) - z] - \alpha D(s)\}\alpha D(s)}_{\text{demand side delay cost}} - \underbrace{\theta f D(s)}_{\text{supply side delay cost}} + \frac{1}{4}\eta[\bar{b} - \tau + a(s) - z]^2 - \delta f. \end{aligned} \quad (6)$$

The optimal fare increases with the private benefit of traveling for passengers and with the marginal cost to produce the transport service. Note that the optimal fare is increasing with the passengers' utility gain from a safety standard and decreasing with the delays. Finally, the higher the value of the outside option, the lower the optimal fare.

According to the optimal profit of the airline, delays will play a role both in airline cost and consumer demand. With long delays, the same quantity of transport service (that is, the number of passengers) is to be operated at a lower price. However, costs also increase, and consequently, it may be less and less profitable for the airline to operate traffic. If airlines greatly value delays, they may be interested in buying contracts that enable a fixed and reduced exposure to delays. We thus introduce ANSP, which will maximize the social welfare (or its profit).

We then obtain the passenger utility and surplus as follows:

$$\begin{aligned} v^*(s) &= y - p^*(s) + b + a(s) - \alpha D(s), \\ ps^*(s) &= \underbrace{\int_{p^*(s)-a(s)+\alpha D(s)+z}^{\bar{b}} [y - p^*(s) + b + a(s) - \alpha D(s)]\eta\, db}_{\text{consumers travelling}} + \underbrace{\int_{\underline{b}}^{p^*(s)-a(s)+\alpha D(s)+z} (y+z)\eta\, db}_{\text{consumers using other modes of transport}} \\ &= \underbrace{-\frac{1}{8}\eta\{2[\bar{b} - \tau + a(s) - z] - \alpha D(s)\}\alpha D(s)}_{\text{pass enger delay impacton welfare}} + \frac{1}{8}\eta[\bar{b} + \tau - a(s) + z]^2 - \frac{1}{2}\eta\bar{b}[\bar{b} + \tau - a(s) - z] + \frac{1}{2}\eta\bar{b}^2 - \eta\underline{b}(y+z) + \eta\bar{b}y. \end{aligned} \quad (7)$$

ANSP makes a take-it-or-leave-it offer (a contract) to the airline, in which contracting variables are r and t. $r \in [0, 1]$ is the degree of the delay reduction service that ANSP provides to the airline, and t is the payment transfer from the airline to ANSP. After signing the contract, the expected delays per flight reduce from $D(s)$ to $D(s)[1 - R(\sigma, r)]$, in which $R(\sigma, r)$ is the fraction of delay reduction and σ measures the effectiveness of the service. It is assumed that $\partial R(\sigma, r)/\partial \sigma > 0$, $\partial R(\sigma, r)/\partial r > 0$, and $\partial^2 R(\sigma, r)/\partial r^2 < 0$, in which the last two derivatives capture that the marginal value of the service is positive but decreasing with the degree. In order to obtain analytical results, it is assumed that $R(\sigma, r) \equiv \sigma \ln(1 + r)$, with $\sigma \in [0, 1/\ln 2]$. The fare, air traffic, airline profit, passenger utility, and passenger surplus will then be as follows:

$$
\begin{aligned}
P^*(s, r) &= p^*(s) + \frac{1}{2}\alpha\, D(s)\sigma \ln(1 + r),\\
Q^*(s, r) &= q^*(s) + \frac{1}{2}\eta\alpha\, D(s)\sigma \ln(1 + r),\\
\Pi^*(\theta, s, r) &= \underbrace{\pi^*(\theta, s)}_{\text{initial profit}} + \underbrace{\frac{1}{4}\eta\alpha^2 D(s)^2\sigma^2[\ln(1 + r)]^2 + q^*(s)\alpha\, D(s)\sigma\ln(1 + r)}_{\text{demand side delay reduction benefit}} + \underbrace{\theta f\, D(s)\sigma\ln(1 + r)}_{\text{supply side delay reduction benefit}},\\
V^*(s, r) &= v^*(s) + \frac{1}{2}\alpha\, D(s)\sigma\ln(1 + r),\\
PS^*(s, r) &= \underbrace{ps^*(s)}_{\text{initial passenger surplus}} + \underbrace{\frac{1}{2}\left\{\frac{1}{4}\eta\alpha^2 D(s)^2\sigma^2[\ln(1 + r)]^2 + q^*(s)\alpha\, D(s)\sigma\ln(1 + r)\right\}}_{\text{passenger delay reduction benefit}}.
\end{aligned}
\tag{8}
$$

, respectively. These results show that the airline can enjoy both demand and supply-side delay reduction benefits and that the passengers can enjoy higher surplus, even though the fare increases.

Finally, ANSP's cost of providing the service (another feasible setup is the linear benefit and convex cost, which is essentially equivalent to our setting, that is, the concave benefit and linear cost) is as follows:

$$C_{ANSP}(s, r) = m(s)r. \tag{9}$$

In equation (9), $m(s)$ is the marginal cost of the service, which increases with the safety standard, that is, $m'(s) \geq 0$ (see [43]). In fact, when providing the service, the ANSP has to spend more time on evaluation and coordination in order to satisfy a higher safety standard, which will inevitably result in a higher cost.

The timeline of the model is shown in Figure 1.

3. Optimal Contracts

In this section, we derive optimal contracts by considering both the welfare- and profit-maximizing ANSPs. Note that we focus the following discussions on interior solutions.

3.1. Welfare-Maximizing ANSP. The welfare-maximizing ANSP's objective is as follows:

$$
\begin{aligned}
\max_{\{(r,t)\}} W = {} & PS^*(s, r) + \Pi^*(\theta, s, r) - C_{ANSP}(s, r)\\
& - \lambda[C_{ANSP}(s, r) - t]1_{t<C(s,r)}.
\end{aligned}
\tag{10}
$$

Here, λ is the shadow cost of public funds. Note that when the transfer t is not enough to cover the total cost of providing the service $C_{ANSP}(s, r)$ and the social values of the service are nonnegative, that is, $[PS^*(s, r) - ps^*(s)] + [\Pi^*(\theta, s, r) - \pi^*(\theta, s)] - C_{ANSP}(s, r) - \lambda[C_{ANSP}(s, r) - t]1_{t<C(s,r)} \geq 0$, public funds should be used to cover the gap between t and $C_{ANSP}(s, r)$ but at some costs (shadow costs of public funds).

Passengers' value of time will be a determinant for the existence of an air transport market, as shown in Lemma 1.

Lemma 1. *Existence of the air transport market. If passengers place a lot of importance on the event of being delayed, then they will always choose another mode of transportation. Hence, the air transport market exists if* $\alpha \leq \overline{b} - \tau + a(s) - z/D(s)$.

Proof. In Appendix B.1.

As there might exist a distinction between the benefits of the monopoly airline and the welfare-maximizing ANSP, in the case of welfare-maximizing ANSP, we have to distinguish between two scenarios, that is, the "high airline benefit" and the "low airline benefit." For a welfare-maximizing ANSP, the sum of the airline profit, passenger surplus, and the cost of providing the delay reduction service are maximized. Therefore, if the social benefit of the airline and passengers derived from a delay reduction service is larger than the social cost of ANSP providing the delay reduction service, the welfare-maximizing ANSP should always provide the delay reduction service.

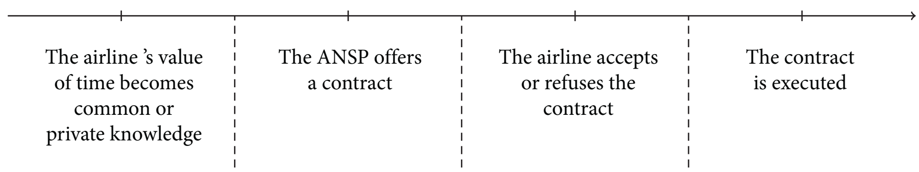

FIGURE 1: Timeline.

In fact, both the airline and passengers benefit from the service, but only the airline pays for the service. Hence, if the airline's benefit from the service is higher than ANSP's cost of providing the service, the transfer from the airline to ANSP could be enough to cover ANSP's cost. This is the case in scenario 1 (high airline benefit). However, if the airline's benefit from the service is lower than ANSP's cost of providing the service, the airline's transfer will never be enough to cover ANSP's cost (note that the highest transfer equals the airline's benefit from the service), and therefore, ANSP will have to use public funds to provide the delay reduction service at some cost. This is the case in scenario 2 (low-airline benefit). □

3.1.1. Scenario 1: High-Airline Benefit. In this scenario, both passengers and the airline benefit from the service and the airline's benefit are higher than ANSP's cost of providing the service. Hence, the delay reduction contract could be implemented without using public funds. However, the problem here is to quantify under incomplete information the importance of the information rent. Let us start with a complete information setting.

(1) Complete Information. Under complete information, it is optimal for ANSP to set the transfer at least as the cost of providing the service. Accordingly, the optimization problem of the ANSP is as follows:

$$\max_{\{r\}} W = PS^*(s,r) + \Pi^*(\theta,s,r) - C_{ANSP}(s,r). \qquad (11)$$

Then, by taking the first-order condition of equation (11), we can obtain that the first-best (FB) optimal contracts for the airline with $\overline{\theta}$ and $\underline{\theta}$ are $\{(\overline{r}^{FB},\overline{t}^{FB})\}$ and $\{(\underline{r}^{FB},\underline{t}^{FB})\}$, respectively. In particular, as shown in (12), $\overline{r}^{FB}$ and $\underline{r}^{FB}$ are determined by $\overline{\Omega}=0$ and $\underline{\Omega}=0$, respectively. These two implicit functions define the optimal degrees of the delay reduction service in contracts. For both $\overline{\Omega}$ and $\underline{\Omega}$, the optimal degree is determined by the intersection of a logarithmic and linear function of r. According to $\overline{\Omega}=0$ and $\underline{\Omega}=0$ in equation (12), because $\overline{\theta}>\underline{\theta}$, we also have $\overline{r}^{FB}>\underline{r}^{FB}$. A detailed discussion about the second-order condition of equation (11) is in Appendix A. Discussions about other second-order conditions in this study are similar and are, therefore, omitted hereafter. In addition, $\overline{t}^{FB}$ and $\underline{t}^{FB}$ are given as follows:

$$\begin{cases} \overline{\Omega} & \equiv 3\eta\alpha^2 D(s)^2\sigma^2\ln\left(1+\overline{r}^{FB}\right)-\left\{4m(s)\left(1+\overline{r}^{FB}\right)-3\eta[\overline{b}-\tau+a(s)-z-\alpha\ D(s)]\alpha\ D(s)\sigma-4\overline{\theta}f\ D(s)\sigma\right\}=0,\\ \overline{t}^{FB} & \in\left[m(s)\overline{r}^{FB},\Pi^*\left(\overline{\theta},s,\overline{r}^{FB}\right)-\pi^*\left(\overline{\theta},s\right)\right],\\ \underline{\Omega} & \equiv 3\eta\alpha^2 D(s)^2\sigma^2\ln\left(1+\underline{r}^{FB}\right)-\left\{4m(s)\left(1+\underline{r}^{FB}\right)-3\eta[\overline{b}-\tau+a(s)-z-\alpha\ D(s)]\alpha\ D(s)\sigma-4\underline{\theta}f\ D(s)\sigma\right\}=0,\\ \underline{t}^{FB} & \in\left[m(s)\underline{r}^{FB},\Pi^*\left(\underline{\theta},s,\underline{r}^{FB}\right)-\pi^*\left(\underline{\theta},s\right)\right]. \end{cases} \qquad (12)$$

(2) Incomplete Information. Under incomplete information, the first-best optimal degrees of the service can be feasible and induced costs for ANSP are covered (without the need to leverage public funds). Indeed, the benefits of delay reduction together with passengers and the airline are enough to compensate the costs of providing the delay reduction service.

ANSP maximizes the expected social welfare as follows:

$$\max_{\{(\overline{r},\underline{r})\}} W = \mu\left[PS^*(s,\overline{r})+\Pi^*(\overline{\theta},s,\overline{r})-C_{ANSP}(s,\overline{r})\right] + (1-\mu)\left[PS^*(s,\underline{r})+\Pi^*(\underline{\theta},s,\underline{r})-C_{ANSP}(s,\underline{r})\right]. \qquad (13)$$

For feasible separating contracts, the airline's incentive compatibility and participation constraints must be satisfied, that is,

$$\begin{aligned} &\Pi^*(\overline{\theta},s,\overline{r})-\overline{t}\geqslant\Pi^*\left(\overline{\theta},s,\underline{r}\right)-\underline{t},\\ &\Pi^*(\underline{\theta},s,\underline{r})-\underline{t}\geqslant\Pi^*(\underline{\theta},s,\overline{r})-\overline{t},\\ &\Pi^*(\overline{\theta},s,\overline{r})-\overline{t}\geqslant\pi^*(\overline{\theta},s),\\ &\Pi^*(\underline{\theta},s,\underline{r})-\underline{t}\geqslant\pi^*(\underline{\theta},s). \end{aligned} \qquad (14)$$

The information rent of the airline is denoted with $\overline{\theta}$ and $\underline{\theta}$ by $\overline{u}$ and $\underline{u}$, respectively, in which $\overline{u}=\Pi^*(\overline{\theta},s,\overline{r})-\pi^*(\overline{\theta},s)-\overline{t}$ and $\underline{u}=\Pi^*(\underline{\theta},s,\underline{r})-\pi^*$

$(\underline{\theta}, s) - \underline{t}$. Then, we can write the airline's incentive compatibility and participation constraints as follows:

$$\begin{aligned}&\overline{u} \geqslant \underline{u} + \Delta\theta f\ D(s)\sigma \ln(1+\underline{r}),\\&\underline{u} \geqslant \overline{u} - \Delta\theta f\ D(s)\sigma \ln(1+\overline{r}),\\&\overline{u} \geqslant 0,\\&\underline{u} \geqslant 0.\end{aligned} \tag{15}$$

In order to solve the ANSP's problem, first $\overline{u} \geqslant \underline{u} + \Delta\theta f\ D(s)\sigma \ln(1+\underline{r})$ should be made, $\underline{u} \geqslant 0$ should be binding, $\underline{u} \geqslant \overline{u} - \Delta\theta f\ D(s)\sigma \ln(1+\overline{r})$ and $\overline{u} \geqslant 0$ should be omitted, and then the omitted constraints should be checked after solving the problem. The simplified constraints become $\overline{u} = \Delta\theta f\ D(s)\sigma \ln(1+\underline{r})$ and $\underline{u} = 0$.

In fact, the maximization of equation (13) gives the same optimal degrees of the service as under complete information, that is, $\overline{r}^{FB}$ and $\underline{r}^{FB}$ determined by $\overline{\Omega} = 0$ and $\underline{\Omega} = 0$ in equation (12). Furthermore, the second-best (SB) optimal degrees $\overline{r}^{SB} = \overline{r}^{FB}$ and $\underline{r}^{SB} = \underline{r}^{FB}$ can satisfy the omitted constraints $\underline{u} \geqslant \overline{u} - \Delta\theta f\ D(s)\sigma \ln(1+\overline{r})$ and $\overline{u} \geqslant 0$. According to $\overline{u} = \Delta\theta f\ D(s)\sigma \ln(1+\underline{r})$ and $\underline{u} = 0$, the second-best optimal transfers are as follows:

$$\begin{cases}\overline{t}^{SB} = \Pi^*\left(\overline{\theta}, s, \overline{r}^{FB}\right) - \pi^*(\overline{\theta}, s) - \Delta\theta f\ D(s)\sigma \ln\left(1 + \underline{r}^{FB}\right),\\ \underline{t}^{SB} = \Pi^*\left(\underline{\theta}, s, \underline{r}^{FB}\right) - \pi^*(\underline{\theta}, s).\end{cases} \tag{16}$$

as long as $\overline{t}^{SB} \geqslant C_{ANSP}(s, \underline{r}^{FB})$. Furthermore, as shown in $\overline{t}^{SB}$ in equation (16), ANSP provides an information rent $\Delta\theta f\ D(s)\sigma \ln(1+\underline{r}^{FB})$ to the airline with $\overline{\theta}$ in order to avoid it mimicking the other type.

If $\overline{t}^{SB} < C_{ANSP}(s, \underline{r}^{FB})$, ANSP may still propose separating contracts by using public funds or propose a pooling contract without using public funds. The separating contracts are more effective than the pooling contract in terms of efficiency, while the pooling contract saves the cost of public funds. As the optimality between these two types of contracts depends on parameter values, it will be an issue in practice.

3.1.2. Scenario 2: Low-Airline Benefit. In this scenario, both passengers and the airline can benefit from the service and the airline's benefit is lower than ANSP's cost of providing the service. Therefore, as long as the social benefit of the service outweighs the social cost, it is optimal for ANSP to use public funds (even at shadow cost λ) to cover the part of the costs, which cannot be covered by the airline's transfer.

Because the analysis for $\overline{r}^{FB}$ and $\underline{r}^{FB}$ under complete information is similar to that in Scenario 1, we will only derive optimal contracts under incomplete information.

(1) Incomplete Information. Under incomplete information, ANSP maximizes the expected social welfare as follows:

$$\begin{aligned}\max_{\{(\overline{r},\overline{t});\,(\underline{r},\underline{t})\}} W = {}& \mu\left\{PS^*(s,\overline{r}) + \Pi^*(\overline{\theta}, s, \overline{r}) - C_{ANSP}(s,\overline{r}) - \lambda\left[C_{ANSP}(s,\overline{r}) - \overline{t}\right]\right\}\\&+ (1-\mu)\left\{PS^*(s,\underline{r}) + \Pi^*(\underline{\theta}, s, \underline{r}) - C_{ANSP}(s,\underline{r}) - \lambda\left[C_{ANSP}(s,\underline{r}) - \underline{t}\right]\right\},\end{aligned} \tag{17}$$

subject to the airline's incentive compatibility and participation constraints, as shown in Scenario 1.

Following the same procedure of derivation as in Scenario 1, plugging $\overline{t} = \Pi^*(\overline{\theta}, s, \overline{r}) - \pi^*(\overline{\theta}, s) - \Delta\theta f\ D(s)\sigma \ln(1+\underline{r})$ and $\underline{t} = \Pi^*(\underline{\theta}, s, \underline{r}) - \pi^*(\underline{\theta}, s)$ into (11) and taking the first-order condition of equation (11), we can obtain the second-best optimal menu of contracts $\left\{(\overline{r}^{SB}, \overline{t}^{SB}), (\underline{r}^{SB}, \underline{t}^{SB})\right\}$, as shown in equation (12). Again, $\overline{r}^{SB}$ and $\underline{r}^{SB}$ are determined by the intersection of a logarithmic and linear function and satisfy the omitted constraints. In addition, the second-order condition is also satisfied.

$$\begin{cases} \overline{\Omega} \equiv (3+2\lambda)\eta\alpha^2 D(s)^2\sigma^2 \ln\left(1+\overline{r}^{SB}\right) - \left\{4(1+\lambda)m(s)\left(1+\overline{r}^{SB}\right)\right. \\ -(3+2\lambda)\eta[\overline{b}-\tau+a(s)-z-\alpha D(s)]\alpha D(s)\sigma \\ \left. -4(1+\lambda)\overline{\theta} f D(s)\sigma\right\} = 0, \\ \overline{t}^{SB} = \frac{1}{4}\eta\alpha^2 D(s)^2\sigma^2\left[\ln\left(1+\overline{r}^{SB}\right)\right]^2 + \left\{\frac{1}{2}\eta[\overline{b}-\tau+a(s)-z-\alpha D(s)]\alpha\right. \\ \left. +\overline{\theta} f\right\} D(s)\sigma\ln\left(1+\overline{r}^{SB}\right) - \Delta\theta f D(s)\sigma\ln\left(1+\underline{r}^{SB}\right), \\ \underline{\Omega} \equiv (3+2\lambda)\eta\alpha^2 D(s)^2\sigma^2\ln\left(1+\underline{r}^{SB}\right) - \left\{4(1+\lambda)m(s)\left(1+\underline{r}^{SB}\right)\right. \\ -(3+2\lambda)\eta[\overline{b}-\tau+a(s)-z-\alpha D(s)]\alpha D(s)\sigma \\ \left. -4(1+\lambda)\underline{\theta} f D(s)\sigma + 4\frac{\mu}{1-\mu}\lambda\Delta\theta f D(s)\sigma\right\} = 0, \\ \underline{t}^{SB} = \frac{1}{4}\eta\alpha^2 D(s)^2\sigma^2\left[\ln\left(1+\underline{r}^{SB}\right)\right]^2 + \left\{\frac{1}{2}\eta[\overline{b}-\tau+a(s)-z-\alpha D(s)]\alpha\right. \\ \left. +\underline{\theta} f\right\} D(s)\sigma\ln\left(1+\underline{r}^{SB}\right). \end{cases} \tag{18}$$

According to equation (18), for the optimal degrees of the service we can obtain $\overline{r}^{SB} = \overline{r}^{FB}$ and $\underline{r}^{SB} < \underline{r}^{FB}$. In particular, there is no distortion for the airline with $\overline{\theta}$, while there is a downward distortion for the one with $\underline{\theta}$. Here, we also have $\overline{r}^{SB} > \underline{r}^{SB}$. In addition, only the airline with $\overline{\theta}$ can get a positive information rent $\Delta\theta f\ D(s)\sigma\ln(1+\underline{r}^{SB})$. In fact, under incomplete information, the optimal degree for the airline with $\underline{\theta}$ is distorted downwards to decrease the information rent of the airline with $\overline{\theta}$, which reflects the trade-off between efficiency and rent extraction.

3.2. Profit-Maximizing ANSP. The profit-maximizing ANSP's objective is to maximize the difference between the transfer and the cost of providing the service, that is,

$$\max_{\{(r,t)\}} H = t - C_{ANSP}(s,r). \tag{19}$$

Next, we will derive optimal contracts under $0 < \alpha \leqslant \overline{b} - \tau + a(s) - z/D(s)$.

3.2.1. Complete Information. Under complete information, the ANSP will set the transfer as the airline's benefit from the service, that is, $t = \Pi^*(\theta,s,r) - \pi^*(\theta,s)$. Accordingly, the optimization problem of the ANSP is as follows:

$$\max_{r} H = \Pi^*(\theta,s,r) - \pi^*(\theta,s) - C_{ANSP}(s,r). \tag{20}$$

Then, by taking the first-order condition of equation (20), we can obtain that the first-best optimal contracts for the airline with $\overline{\theta}$ and $\underline{\theta}$ are $\{(\overline{r}^{FB},\overline{t}^{FB})\}$ and $\{(\underline{r}^{FB},\underline{t}^{FB})\}$, respectively, as shown in equation (21). Again, $\overline{r}^{FB}$ and $\underline{r}^{FB}$ are determined by the intersection of a logarithmic and linear function, and because $\overline{\theta} > \underline{\theta}$, we have $\overline{r}^{FB} > \underline{r}^{FB}$. In addition, the second-order condition can be satisfied as follows:

$$\begin{cases} \overline{\Omega} \equiv \eta\alpha^2 D(s)^2\sigma^2 \ln\left(1+\overline{r}^{FB}\right) - \left\{2m(s)\left(1+\overline{r}^{FB}\right) \right. \\ \quad \left. -\eta[\overline{b}-\tau+a(s)-z-\alpha D(s)]\alpha D(s)\sigma - 2\overline{\theta} f D(s)\sigma \right\} = 0, \\ \overline{t}^{FB} = \frac{1}{4}\eta\alpha^2 D(s)^2\sigma^2\left[\ln\left(1+\overline{r}^{FB}\right)\right]^2 + \left\{\frac{1}{2}\eta[\overline{b}-\tau+a(s)-z-\alpha D(s)]\alpha \right. \\ \quad \left. +\overline{\theta} f\right\} D(s)\sigma \ln\left(1+\overline{r}^{FB}\right), \\ \underline{\Omega} \equiv \eta\alpha^2 D(s)^2\sigma^2 \ln\left(1+\underline{r}^{FB}\right) - \left\{2m(s)\left(1+\underline{r}^{FB}\right) \right. \\ \quad \left. -\eta[\overline{b}-\tau+a(s)-z-\alpha D(s)]\alpha D(s)\sigma - 2\underline{\theta} f D(s)\sigma \right\} = 0, \\ \underline{t}^{FB} = \frac{1}{4}\eta\alpha^2 D(s)^2\sigma^2\left[\ln\left(1+\underline{r}^{FB}\right)\right]^2 + \left\{\frac{1}{2}\eta[\overline{b}-\tau+a(s)-z-\alpha D(s)]\alpha \right. \\ \quad \left. +\underline{\theta} f\right\} D(s)\sigma \ln\left(1+\underline{r}^{FB}\right). \end{cases} \tag{21}$$

3.2.2. Incomplete Information. Under incomplete information, ANSP maximizes the expected profit as follows:

$$\max_{\{(\overline{r},\overline{t});\,(\underline{r},\underline{t})\}} H = \mu\left[\overline{t} - C_{ANSP}(s,\overline{r})\right] + (1-\mu)\left[\underline{t} - C_{ANSP}(s,\underline{r})\right], \tag{22}$$

subject to the airline's incentive compatibility and participation constraints as shown in Scenario 1 of welfare-maximizing ANSP.

Then, by taking the first-order condition of equation (22), we can obtain the second-best optimal menu of contracts $\left\{(\overline{r}^{SB}, \overline{t}^{SB}), (\underline{r}^{SB}, \underline{t}^{SB})\right\}$, as shown in equation (23).

Again, $\overline{r}^{SB}$ and $\underline{r}^{SB}$ are determined by the intersection of a logarithmic and linear function and can satisfy omitted constraints. In addition, the second-order condition can be satisfied as follows:

$$\begin{cases} \overline{\Omega} & \equiv \eta\alpha^2 D(s)^2\sigma^2 \ln\left(1+\overline{r}^{SB}\right) - \left\{2m(s)\left(1+\overline{r}^{SB}\right)\right. \\ & \left. -\eta[\overline{b}-\tau+a(s)-z-\alpha\, D(s)]\alpha\, D(s)\sigma - 2\overline{\theta} f\, D(s)\sigma\right\} = 0, \\ \overline{t}^{SB} & = \frac{1}{4}\eta\alpha^2 D(s)^2\sigma^2\left[\ln\left(1+\overline{r}^{SB}\right)\right]^2 + \left\{\frac{1}{2}\eta[\overline{b}-\tau+a(s)-z-\alpha\, D(s)]\alpha\right. \\ & \left. +\overline{\theta} f\right\} D(s)\sigma\ln\left(1+\overline{r}^{SB}\right) - \Delta\theta f\, D(s)\sigma\ln\left(1+\underline{r}^{SB}\right), \\ \underline{\Omega} & \equiv \eta\alpha^2 D(s)^2\sigma^2\ln\left(1+\underline{r}^{SB}\right) - \left\{2m(s)\left(1+\underline{r}^{SB}\right)\right. \\ & -\eta[\overline{b}-\tau+a(s)-z-\alpha\, D(s)]\alpha\, D(s)\sigma - 2\underline{\theta} f\, D(s)\sigma \\ & \left. +2\frac{\mu}{1-\mu}\Delta\theta f\, D(s)\sigma\right\} = 0, \\ \underline{t}^{SB} & = \frac{1}{4}\eta\alpha^2 D(s)^2\sigma^2\left[\ln\left(1+\underline{r}^{SB}\right)\right]^2 + \left\{\frac{1}{2}\eta[\overline{b}-\tau+a(s)-z-\alpha\, D(s)]\alpha\right. \\ & \left. +\underline{\theta} f\right\} D(s)\sigma\ln\left(1+\underline{r}^{SB}\right). \end{cases} \tag{23}$$

According to equation (15) and equation (17), for the optimal degrees of the service, we can obtain $\overline{r}^{SB} = \overline{r}^{FB}$ and $\underline{r}^{SB} < \underline{r}^{FB}$. In particular, there is no distortion for the airline with $\overline{\theta}$, while there is a downward distortion for the one with $\underline{\theta}$. Here, we also have $\overline{r}^{SB} > \underline{r}^{SB}$. Moreover, only the airline with $\overline{\theta}$ can get a positive information rent $\Delta\theta f\ D(s)\sigma\ln(1+\underline{r}^{SB})$.

4. Adjustments of Optimal Contracts

Because contracts should be adjusted over time according to the evolution of relevant exogenous variables, we will study the effects of safety standard and flight frequency on optimal contracts. Furthermore, we will use the optimal contracts under incomplete information in Scenario 2 of welfare-maximizing ANSP as an example. For other optimal contracts, the analysis is similar and, therefore, omitted hereafter.

As we do not have explicit solutions for the optimal degree of the service, we will use derivatives of implicit functions. *LOGR* and *LR* are used to denote the logarithmic and linear functions, respectively. In particular, for a variable x_l $(l = 1, 2, \ldots, L)$, we have $\partial r/\partial x_l = -(\partial\Omega/\partial x_l)/(\partial\Omega/\partial r)$. Since $\partial\Omega/\partial r = \text{slope}(LOGR) - \text{slope}(LR) < 0$ must hold for any optimal degree, the sign of $\partial r/\partial x_l$ is the same as that of $\partial\Omega/\partial x_l$. That is, in order to see the effect of a variable on the optimal degree, we need to study its effect on the implicit function that determines the optimal degree.

4.1. Effect of Safety Standard

4.1. Effect of Safety Standard. Undoubtedly, safety is the highest priority in the air transport sector and the safety standard is always increasing. Consequently, it is worth studying how the improvement in safety standards affects optimal degrees. We first give a definition.

Definition 1. The safety elasticity of delays and the safety elasticity of cost are defined as, respectively,

$$\varepsilon_{gs} \equiv \frac{dg(s)}{g(s)}\frac{s}{ds}, \qquad \varepsilon_{ms} \equiv \frac{dm(s)}{m(s)}\frac{s}{ds}. \tag{24}$$

The safety elasticity of delays (resp. cost) measures the percentage change in delays caused by an exceptional event (the marginal cost of the service) in response to a one percent change in safety standard.

Let $\overline{\varepsilon}^{SB}(\overline{r}^{SB})$ and $\underline{\varepsilon}^{SB}(\underline{r}^{SB})$ denote two thresholds, in which

$$\overline{\varepsilon}^{SB}\left(\overline{r}^{SB}\right) \equiv -\frac{(3+2\lambda)\eta\alpha\, D(s)\sigma s}{2(1+\lambda)\left(1+\overline{r}^{SB}\right)m(s)}\frac{\partial\overline{V}^{*}\left(s,\overline{r}^{SB}\right)}{\partial s},$$

$$\underline{\varepsilon}^{SB}\left(\underline{r}^{SB}\right) \equiv -\frac{(3+2\lambda)\eta\alpha\, D(s)\sigma s}{2(1+\lambda)\left(1+\underline{r}^{SB}\right)m(s)}\frac{\partial\underline{V}^{*}\left(s,\underline{r}^{SB}\right)}{\partial s}. \quad (25)$$

Then, we obtain Proposition 1.

Proposition 1. *For the effect of the improvement of safety standard s on the degree of delay reduction service r:*

(1) $\overline{r}^{SB}$ *increases with s if and only if* $\varepsilon_{gs}-\varepsilon_{ms} \geq \overline{\varepsilon}^{SB}(\overline{r}^{SB})$

(2) $\underline{r}^{SB}$ *increases with s if and only if* $\varepsilon_{gs}-\varepsilon_{ms} \geq \underline{\varepsilon}^{SB}(\underline{r}^{SB})$

Proof. We first consider the effect of s on $\overline{r}^{SB}$. According to equation (18), we have the following:

$$\frac{\partial\overline{\Omega}}{\partial s} = \left\{2(3+2\lambda)\eta\alpha^2 D(s)\sigma^2\ln\left(1+\overline{r}^{SB}\right) - (3+2\lambda)\eta\alpha^2 D(s)\sigma + (3+2\lambda)\eta\left[\overline{b}-\tau+a(s)-z-\alpha\, D(s)\right]\alpha\sigma + 4(1+\lambda)\overline{\theta} f\sigma\right\} \cdot 2\left[\sum_{k=1}^{+\infty}\frac{(\beta T/f)^k e^{-(\beta T/f)}}{(k-1)!} + \gamma\beta\frac{f}{T}\right]g'(s) + (3+2\lambda)\eta\alpha\, D(s)\sigma a'(s) - 4(1+\lambda)\left(1+\overline{r}^{SB}\right)m'(s). \quad (26)$$

By using ε_{gs}, ε_{ms}, and equation (18), $\partial\overline{\Omega}/\partial s$ becomes

$$\frac{\partial\overline{\Omega}}{\partial s} = \frac{1}{s}\left\{4(1+\lambda)\left(1+\overline{r}^{SB}\right)m(s)\left(\varepsilon_{gs}-\varepsilon_{ms}\right) + (3+2\lambda)\eta\alpha\, D(s)\sigma\left\{a'(s)s - \alpha\, D(s)\left[1-\sigma\ln\left(1+\overline{r}^{SB}\right)\right]\varepsilon_{gs}\right\}\right\}. \quad (27)$$

Next, introducing the direct effect of the improvement of safety standard on passenger utility, that is,

$$\begin{aligned}\frac{\partial\overline{V}^{*}\left(s,\overline{r}^{SB}\right)}{\partial s} &= \frac{1}{2}\left\{a'(s) - 2\alpha\left[\sum_{k=1}^{+\infty}\frac{(\beta T/f)^k e^{-(\beta T/f)}}{(k-1)!} + \gamma\beta\frac{f}{T}\right]\left[1-\sigma\ln\left(1+\overline{r}^{SB}\right)\right]g'(s)\right\} \\ &= \frac{1}{2s}\left\{a'(s)s - \alpha\, D(s)\left[1-\sigma\ln\left(1+\overline{r}^{SB}\right)\right]\varepsilon_{gs}\right\}.\end{aligned} \quad (28)$$

and plugging $\partial\overline{V}^{*}(s,\overline{r}^{SB})/\partial s$ into $\partial\overline{\Omega}/\partial s$, we can obtain the first point of Proposition 1.

We can analogously obtain the second point.

According to Proposition 1, the optimal degree of the service increases with the safety standard if and only if the difference between the safety elasticity of delays and cost is greater than a threshold, which is a function of the direct effect of the improvement of safety standard on passenger utility. In addition, if passengers can directly benefit from a higher safety standard, the threshold will be negative. In order to illustrate the first point of Proposition 1, we analyze the effects of safety standards in equation (26). In particular, the improvement in safety standards implies longer delays caused by an exceptional event, a higher passengers' utility gain, and a higher marginal cost of the service. The first term in equation (26) shows a direct and an indirect effect of longer delays caused by an exceptional event on the degree of the service. On the one hand, longer delays will increase the marginal benefit of the service to society and thus give ANSP a direct incentive to increase the degree. ε_{gs} in the first point represents part of this direct effect. On the other hand, longer delays will decrease the air traffic, which implies a lower marginal benefit of the service to society, and, therefore, give ANSP an indirect incentive to decrease the degree. In the second term, the higher utility gain will increase the air traffic, which implies a higher marginal benefit of the service to society, and, thus, give ANSP an indirect incentive to increase the degree. In addition, in the third term, the higher marginal cost of the service gives ANSP a direct incentive to decrease the degree. ε_{ms} in the first point represents this direct effect. Finally, the condition in the first point is the synthesis of the effects above, which, more precisely, is about whether or not the effects conducive to the increase in the degree can dominate the others.

We can analogously illustrate the second point, although we consider another effect in terms of the information rent. In particular, longer delays caused by an exceptional event will increase the information rent of the airline with $\overline{\theta}$, which is a function of $\underline{r}^{SB}$, and, therefore, give the ANSP an indirect incentive to decrease $\underline{r}^{SB}$.

Next, as we discuss the effects of the improvement of safety standards through longer delays caused by an exceptional event, we also extend our analysis to study how the longer expected delays per flight affect optimal degrees. Let $\overline{\alpha}^{SB}(\overline{r}^{SB})$ and $\underline{\alpha}^{SB}(\underline{r}^{SB})$ denote two thresholds, in which

$$\overline{\alpha}^{SB}\left(\overline{r}^{SB}\right) \equiv \frac{2}{D(s)}\sqrt{\frac{(1+\lambda)m(s)\left(1+\overline{r}^{SB}\right)}{(3+2\lambda)\eta\sigma\left[1-\sigma\ln\left(1+\overline{r}^{SB}\right)\right]}},$$
$$\underline{\alpha}^{SB}\left(\underline{r}^{SB}\right) \equiv \frac{2}{D(s)}\sqrt{\frac{(1+\lambda)m(s)\left(1+\underline{r}^{SB}\right)}{(3+2\lambda)\eta\sigma\left[1-\sigma\ln\left(1+\underline{r}^{SB}\right)\right]}}. \quad (29)$$

Then, we obtain Proposition 2. □

Proposition 2. *For the effect of the change in expected delays per flight $D(s)$ on the degree of delay reduction service r:*

(1) $\overline{r}^{SB}$ increases with $D(s)$ if and only if $\alpha \leqslant \overline{\alpha}^{SB}(\overline{r}^{SB})$

(2) $\underline{r}^{SB}$ increases with $D(s)$ if and only if $\alpha \leqslant \underline{\alpha}^{SB}(\underline{r}^{SB})$

Proof. In Appendix B.2.

According to Proposition 2, the optimal degree increases with expected delays per flight if and only if the passengers' value of time is lower than a threshold. As shown in the analysis of Proposition 1, longer delays affect optimal degrees mainly through a direct effect (higher marginal benefit of the service to society) and an indirect effect (less traffic). Proposition 2 tells us that if the passengers' value of time is relatively low, the direct effect will dominate the indirect one, and then, optimal degrees will increase. Otherwise, the outside option will be more valuable for passengers. Accordingly, the direct effect will be dominated by the indirect one, and then, optimal degrees will decrease.

Moreover, as $\overline{\alpha}^{SB}(\overline{r}^{SB}) \geqslant \underline{\alpha}^{SB}(\underline{r}^{SB})$, it is possible that when delays become longer, ANSP should adjust optimal degrees in opposite directions. Considering also $\overline{\alpha}^{FB}(\overline{r}^{FB}) \geq \underline{\alpha}^{FB}(\underline{r}^{FB})$ under complete information in Scenario 2 of welfare-maximizing ANSP, we have Corollary 1. □

Corollary 1. *When $D(s)$ becomes longer, if $\underline{\alpha}^{FB}(\underline{r}^{FB}) \leq \alpha \leq \overline{\alpha}^{FB}(\overline{r}^{FB})$ (resp. $\underline{\alpha}^{SB}(\underline{r}^{SB}) \leq \alpha \leq \overline{\alpha}^{SB}(\overline{r}^{SB})$), optimal degrees under complete (resp. incomplete) information will move in opposite directions. Furthermore, $\overline{\alpha}^{SB}(\overline{r}^{SB}) - \underline{\alpha}^{SB}(\underline{r}^{SB}) \geq \overline{\alpha}^{FB}(\overline{r}^{FB}) - \underline{\alpha}^{FB}(\underline{r}^{FB})$ implies that the existence of information rent increases the possibility that optimal degrees move in opposite directions.*

4.2. Effect of Flight Frequency

In this model, because of the slot control in Europe, we assume that flight frequency is not an endogenous decision variable of the airline. Here, we study how the change in flight frequency affects optimal degrees.

We first introduce some notations. According to Proposition 2, $\partial\overline{r}^{SB}/\partial D(s) \geqslant 0$ if and only if $\Phi \geqslant 0$ and $\partial\underline{r}^{SB}/\partial D(s) \geq 0$ if and only if $\Psi \geqslant 0$, in which

$$\Phi \equiv 4(1+\lambda)m(s)\left(1+\overline{r}^{SB}\right) - (3+2\lambda)\eta\alpha^2 D(s)^2\sigma\left[1-\sigma\ln\left(1+\overline{r}^{SB}\right)\right],$$
$$\Psi \equiv 4(1+\lambda)m(s)\left(1+\underline{r}^{SB}\right) - (3+2\lambda)\eta\alpha^2 D(s)^2\sigma\left[1-\sigma\ln\left(1+\underline{r}^{SB}\right)\right]. \quad (30)$$

Moreover, let $\overline{\Gamma}_f$ and $\underline{\Gamma}_f$ denote two thresholds, in which

$$\overline{\Gamma}_f \equiv \Gamma - 2(1+\lambda)\overline{\theta}D(s)^2\sigma\frac{1}{\Phi}\frac{T}{\beta g(s)},$$
$$\underline{\Gamma}_f \equiv \Gamma - 2\left[(1+\lambda)\underline{\theta} - \frac{\mu}{1-\mu}\lambda\Delta\theta\right]D(s)^2\sigma\frac{1}{\Psi}\frac{T}{\beta g(s)}, \quad (31)$$
$$\Gamma \equiv \sum_{k=1}^{+\infty}\frac{((\beta T/f))^{k-1}e^{-(\beta T/f)}(k-(\beta T/f))\left(T^2/f^2\right)}{(k-1)!}.$$

In fact, Γ is a threshold such that $\partial D(s)/\partial f \geqslant 0$ if and only if $\gamma \geqslant \Gamma$. Then, we obtain Proposition 3.

Proposition 3. *For the effect of the change in flight frequency f on the degree of delay reduction service r:*

(1) When $\Phi \geqslant$ (resp. $<$) 0, $\overline{r}^{SB}$ increases with f if and only if $\gamma \geqslant$ (resp. $\leqslant$) $\max\left\{0, \overline{\Gamma}_f\right\}$

(2) When $\Psi \geqslant$ (resp. $<$) 0, $\underline{r}^{SB}$ increases with f if and only if $\gamma \geqslant$ (resp. $\leqslant$) $\max\left\{0, \underline{\Gamma}_f\right\}$

Proof. We first consider the effect of f on $\overline{r}^{SB}$. According to equation (18), we have the following:

$$\frac{\partial\overline{\Omega}}{\partial f}\cdot 2\left[-\sum_{k=1}^{+\infty}\frac{(\beta T/f)^k e^{-(\beta T/f)}(k-(\beta T/f))(1/f)}{(k-1)!}g(s) + \gamma\beta\frac{1}{T}g(s)\right]$$
$$+ 4(1+\lambda)\overline{\theta}D(s)\sigma. = \left[2(3+2\lambda)\eta\alpha^2 D(s)\sigma^2\ln\left(1+\overline{r}^{SB}\right) - (3+2\lambda)\eta\alpha^2 D(s)\sigma. \quad (32)$$

By using equation (18), equation (32) becomes

$$\frac{\partial \overline{\Omega}}{\partial f} = \frac{2}{D(s)} \left\{ \left[-\sum_{k=1}^{+\infty} \frac{(\beta T/f)^k e^{-(\beta T/f)} (k - (\beta T/f))(1/f)}{(k-1)!} g(s) + \gamma\beta \frac{1}{T} g(s) \right] \Phi + 2(1+\lambda)\overline{\theta} D(s)^2 \sigma \right\}. \tag{33}$$

Next, using $\overline{\Gamma}_f$, we can obtain the first point of Proposition 3.

We can analogously obtain the second point.

According to Proposition 3, when the optimal degree of the service increases with expected delays per flight, it will increase with flight frequency if and only if the delay externality parameter is greater than a threshold. However, when the optimal degree decreases with expected delays per flight, it will increase with flight frequency if and only if the delay externality parameter is less than a threshold. In order to illustrate the first point of Proposition 3, we should analyze the effects of flight frequency in equation (32). In particular, the increase in flight frequency implies shorter delays due to exceptional events in own slot, longer delays induced by other flights, and a higher supply-side delay reduction benefit of the airline. In equation (32), the first term shows the change in delays, and the second term shows the change in supply-side delay reduction benefit.

The case $\Phi \geqslant 0$ is first considered. In this case, we have $\Gamma \geqslant \overline{\Gamma}_f$. If the externality of delays between flights is significant, that is, $\gamma \geqslant \Gamma$, the delays induced by other flights will dominate the delays due to exceptional events in own slot. Accordingly, expected delays per flight become longer when flight frequency increases. Given $\Phi \geqslant 0$, that is, the direct effect of longer delays (higher marginal benefit of the service to society) dominates the indirect effect of longer delays (less traffic), the net effect shown in the first term in equation (32) is to increase $\overline{r}^{SB}$ when flight frequency increases. Considering also the higher supply-side delay reduction benefit of the airline shown in the second term in equation (32), $\overline{r}^{SB}$ will increase with flight frequency.

However, if the externality of delays between flights is not significant, that is, $\gamma < \Gamma$, the delays induced by other flights will be dominated by the delays due to exceptional events in own slot. Consequently, expected delays per flight become shorter when flight frequency increases, and then, the net effect shown in the first term in equation (32) decreases to $\overline{r}^{SB}$ when flight frequency increases. Next, if $\max\{0, \overline{\Gamma}_f\} \leqslant \gamma < \Gamma$, the effect from the delays due to exceptional events in own slot will be relatively weak, compared with the higher supply-side delay reduction benefit of the airline shown in the second term in equation (32). Then, $\overline{r}^{SB}$ will still increase with flight frequency. Nevertheless, if $\gamma < \max\{0, \overline{\Gamma}_f\}$, the effect from the delays due to exceptional events in own slot will be strong enough. Then, $\overline{r}^{SB}$ will decrease with flight frequency. To summarize, when $\Phi \geqslant 0$, $\overline{r}^{SB}$ will increase with flight frequency if and only if $\gamma \geqslant \max\{0, \overline{\Gamma}_f\}$. Furthermore, we can analogously analyze the case $\Phi < 0$.

In fact, the analysis for the second point of Proposition 3 is similar to that above, except that we should also consider the effect of flight frequency on the information rent of the airline with $\overline{\theta}$. □

5. The Use of Public Funds

For a welfare-maximizing ANSP, when the airline's benefit is higher than ANSP's cost of providing the service (Scenario 1), ANSP may not have to use public funds. However, when the airline's benefit is lower than ANSP's cost of providing the service (Scenario 2), ANSP has to use public funds. Therefore, in this section, by choosing proper parameter values (parameter values used in numerical examples can satisfy all second-order conditions. They can also ensure that the social values of the service are non-negative, that is, $[CS^*(s,r) - cs^*(s)] + [\Pi^*(\theta,s,r) - \pi^*(\theta,s)] - C_{ANSP}(s,r) - \lambda[C_{ANSP}(s,r) - t]1_{t<C(s,r)} \geqslant 0$.) and function specifications, we use numerical examples to study when a welfare-maximizing ANSP has to use public funds to provide the delay reduction service.

In particular, in all numerical examples, we use $a(s) = \ln s/(2\ln 2)$, $g(s) = 0.01 * 2^s$, and $m(s) = 0.06 + 0.01s$. As we can see, $a(s)$ is a concave function of s; $g(s)$ is a convex function of s; and $m(s)$ is a linear function of s. Additionally, we use $\beta = 0.01$, $\gamma = 120$, $\theta = 1$, $\lambda = 0.04$, $N = 2$, $\overline{b} = 3$, $\underline{b} = 1$, $s = 2$, $\tau = 0.8$, $T = 1.5$, $f = 1$, and $z = 2$.

The airline's net benefit is first considered from the service:

$$\omega = \Pi^*(\theta,s,r) - \pi^*(\theta,s) - C_{ANSP}(s,r). \tag{34}$$

which is the net benefit of the airline when it is asked to pay the total cost of providing the service. By using a large number of numerical examples, we find that for each set of parameter values there exists a threshold $\hat{r}$, such that $\omega \geqslant 0$ if and only if $r \leqslant \hat{r}$. Therefore, as long as $r > \hat{r}$, ANSP has to use public funds to provide the service. For example, using $\alpha = 0.35$ and $\sigma = 1/\ln 2$, we can obtain Figure 2.

The marginal benefit of the service to society is denoted by MB, and the marginal cost of the service to ANSP is denoted by MC. If $MB(\hat{r}) \leqslant MC$, in order to make MB equal to MC, ANSP will decrease the degree, and then, the optimal degree will be r^- with $r^- \leqslant \hat{r}$. When $r = r^-$, the airline's benefit is higher than ANSP's cost of providing the service, implying $\omega \geqslant 0$, and therefore, ANSP may not have to use public funds. However, if $MB(\hat{r}) > MC$, in order to make MB equal to MC, ANSP will increase the degree, and then, the optimal degree will be r^+ with $r^+ > \hat{r}$. When $r = r^+$, the airline's benefit is lower than ANSP's cost of providing the service, implying $\omega < 0$, and thus, ANSP has to use public funds.

The next two important parameters should be considered, that is, the passengers' value of time α and the effectiveness of the service σ. Here, we use the following values of α and σ: $\alpha = 0.05\tilde{\alpha}$ with $\tilde{\alpha} \in [0, 50] \cap \mathbb{Z}$ and $\sigma = \tilde{\sigma}/(20\ln 2)$ with $\tilde{\sigma} \in [9, 20] \cap \mathbb{Z}$. For each set of parameter values, we calculate $\hat{r}$. Then, we calculate $MB(\hat{r}) - MC$. If the difference is positive, ANSP has to use

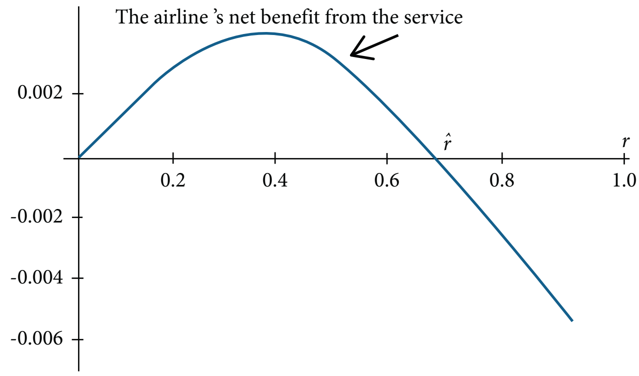

Figure 2: The airline's net benefit from the service. Note: r is the degree of delay reduction service, and $\hat{r}$ is a threshold such that $\omega \geqslant 0$ if and only if $r \leqslant \hat{r}$.

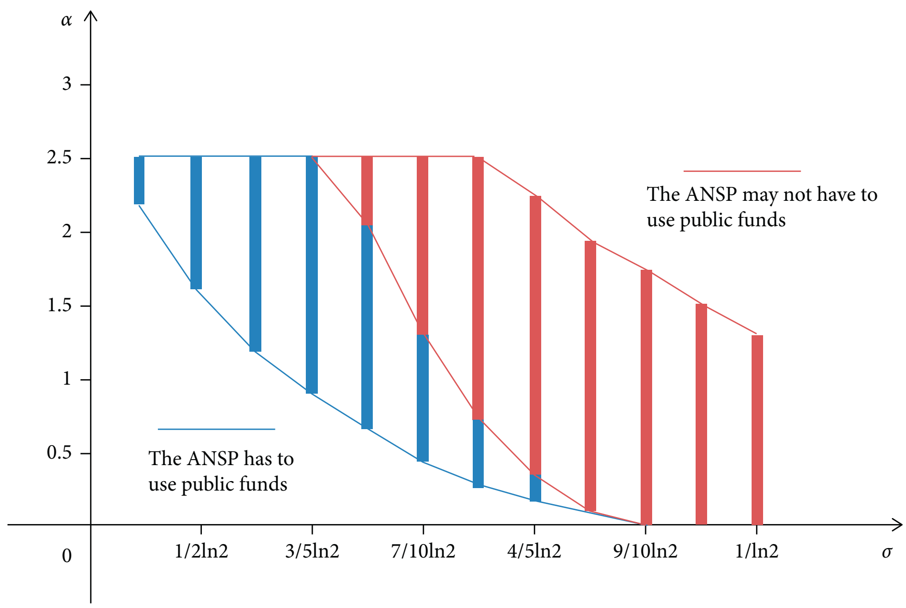

Figure 3: The use of public funds. Note: α is the passengers' value of time, and σ is the effectiveness of delay reduction service.

public funds. Otherwise, ANSP may not have to use public funds. The results of the simulation are shown in Figure 3.

In Figure 3, we find that if σ is high (that is, the service is very effective), the airline can always obtain a high benefit from the service. Consequently, ANSP may not have to use public funds. If σ is low (that is, the service is very ineffective), the airline can only obtain a very limited benefit from the service. Accordingly, ANSP has to use public funds. Finally, if σ falls into an intermediate interval (that is, the effectiveness of the service is intermediate), when the effectiveness decreases, ANSP may not have to use public funds when the passengers' value of time α becomes high enough. Because the passengers' value of time is positively related to the total benefit of the service to society, a higher α can compensate for the loss of benefits resulting from the decrease in the effectiveness of the service.

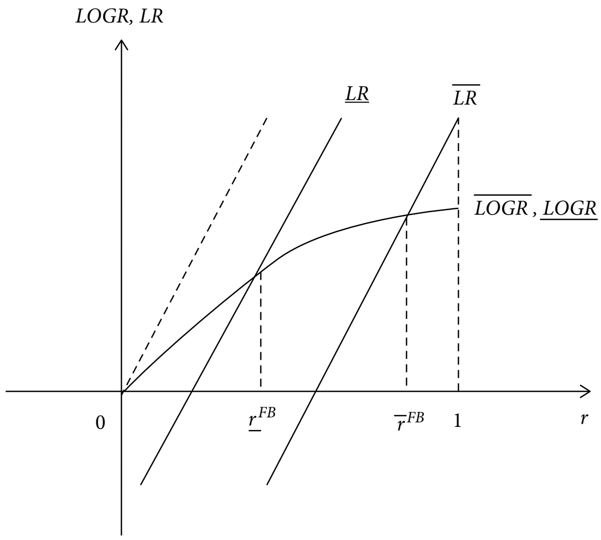

Figure 4: Case 1 (complete information in Scenario 1 of welfare-maximizing ANSP).

6. Conclusions

In the context of the SESAR project, ANSP can provide a delay reduction service to airlines. This study studies the optimal design of a delay reduction contract signed between ANSP and a monopoly airline. In the contract design, the main issue is to address the adverse selection problem, which comes from the airlines' private information about their values of time. We analytically derive optimal contracts by considering both the welfare- and profit-maximizing ANSPs, in which we find that under incomplete information, the optimal degree of the service for the airline with a low value of time may be distorted downwards. Moreover, we conduct a comparative static analysis to study how the changes in safety standard and flight frequency affect optimal contracts. We also use numerical examples to study when a welfare-maximizing ANSP has to use public funds to provide the delay reduction service.

This study focuses on a monopoly airline market structure. A natural extension is to consider the oligopoly airline market structure and to study the strategic interactions between airlines. In addition, in this study, passengers make only a single trip and the passengers' demand is inelastic; therefore, multiple trips and elastic demand are also possible extensions.

Appendix

A. Second-Order Condition in Complete Information in Scenario 1 of Welfare-Maximizing ANSP

In equation (8), the first term of $\overline{\Omega}$ is a logarithmic function of $\overline{r}^{FB}$, and we denote it by $\overline{LOGR}$; the second term of $\overline{\Omega}$ is a linear function of $\overline{r}^{FB}$, and we denote it by $\overline{LR}$. Analogously, the first term of $\underline{\Omega}$ is a logarithmic function of $\underline{r}^{FB}$ and we denote it by $\underline{LOGR}$, and the second term of $\underline{\Omega}$ is a linear function of $\underline{r}^{FB}$ and we denote it by $\underline{LR}$.

Next, we try to confirm the second-order condition of equation (7) according to the slope of the logarithmic and linear functions and the intercept of the linear function on the horizontal axis. Moreover, let I_1 and I_2 denote two expressions indicating the signs of the intercepts, in which

$$\begin{aligned} I_1 &= 4[\overline{\theta} f\ D(s)\sigma - m(s)] \\ &\quad + 3\eta[\overline{b} - \tau + a(s) - z - \alpha\ D(s)]\alpha\ D(s)\sigma, \\ I_2 &= 4[\underline{\theta} f\ D(s)\sigma - m(s)] \\ &\quad + 3\eta[\overline{b} - \tau + a(s) - z - \alpha\ D(s)]\alpha\ D(s)\sigma. \end{aligned} \tag{35}$$

In fact, the second-order condition of equation (7) can be confirmed by considering the following four cases:

Case 1: $0 \leqslant \alpha \leqslant 2/D(s)\sigma\sqrt{m(s)/3\eta}$ and $I_2 \geqslant 0$

Case 2: $2/D(s)\sigma\sqrt{m(s)/3\eta} < \alpha \leqslant \overline{b} - \tau + a(s) - z/D(s)$ and $I_2 \geqslant 0$

Case 3: $2/D(s)\sigma\sqrt{m(s)/3\eta} < \alpha \leqslant \overline{b} - \tau + a(s) - z/D(s)$, $I_1 \geqslant 0$ and $I_2 < 0$

Case 4: $2/D(s)\sigma\sqrt{m(s)/3\eta} < \alpha \leqslant \overline{b} - \tau + a(s) - z/D(s)$ and $I_1 < 0$

Case 1 is shown in Figure 4. $0 < \alpha \leqslant 2/D(s)\sigma\sqrt{m(s)/3\eta}$ is equivalent to $0 < 3\eta\alpha^2 D(s)^2\sigma^2 \leqslant 4m(s)$ and implies that the slope of $\overline{LR}$ (resp. $\underline{LR}$) is greater than that of $\overline{LOGR}$ (resp. $\underline{LOGR}$) for any r. Moreover, $I_2 \geqslant 0$ implies that the signs of $\overline{LR}$'s and $\underline{LR}$'s intercepts on the horizontal axis are positive.

Note: r is the degree of delay reduction service; $LOGR$ is the logarithmic function of r; and LR is the linear function of r.

Because $I_2 \geqslant 0$ and $\overline{\theta} > \underline{\theta}$, we can obtain the following:

$$\begin{aligned} \frac{\partial^2 W}{\partial \overline{r}^2}\Big|_{\overline{r}=\overline{r}^{FB}} &= \frac{1}{4\left(1+\overline{r}^{FB}\right)^2}\left\{3\eta\alpha^2 D(s)^2\sigma^2\left[1-\ln\left(1+\overline{r}^{FB}\right)\right] - 3\eta[\overline{b} - \tau + a(s) - z - \alpha\ D(s)]\alpha\ D(s)\sigma - 4\overline{\theta} f\ D(s)\sigma\right\} \\ &< \frac{1}{4\left(1+\overline{r}^{FB}\right)^2}\left\{3\eta\alpha^2 D(s)^2\sigma^2\left[1-\ln\left(1+\overline{r}^{FB}\right)\right] - 4m(s)\right\}. \end{aligned} \tag{36}$$

Then, according to $0 \leqslant 3\eta\alpha^2 D(s)^2 \sigma^2 \leqslant 4m(s)$, we have $\partial^2 W/\partial \overline{r}^2|_{\overline{r}=\overline{r}^{FB}} < 0$.

Moreover, we can analogously show $\partial^2 W/\partial \underline{r}^2|_{\underline{r}=\underline{r}^{FB}} < 0$.

For cases 2 to 4, we can analogously analyze the following.

B. Proofs

B.1. Proof of Lemma 1

Proof. According to the passenger utility function, a passenger will choose to travel by plane, instead of the outside option, when

$$y - p + b + a(s) - \alpha\ D(s) \geqslant y + z, \tag{37}$$

or

$$b \geqslant p - a(s) + \alpha\ D(s) + z. \tag{38}$$

Given $\overline{b} \geqslant b$ and $p \geqslant \tau$, we can obtain the following:

$$\overline{b} \geqslant b \geqslant p - a(s) + \alpha D(s) + z \geqslant \tau - a(s) + \alpha D(s) + z, \tag{39}$$

which implies

$$\overline{b} \geqslant \tau - a(s) + \alpha D(s) + z. \tag{40}$$

Hence, there exists air traffic at least when

$$\alpha \leq \frac{\overline{b} - \tau + a(s) - z}{D(s)}. \tag{41}$$

□

B.2, Proof of Proposition 2

Proof. We first consider the effect of $D(s)$ on $\overline{r}^{SB}$. According to equation (18), we have the following:

$$\frac{\partial \overline{\Omega}}{\partial D(s)} = \frac{1}{D(s)} \left\{ 4(1+\lambda) m(s) \left(1 + \overline{r}^{SB}\right) - (3 + 2\lambda)\eta\alpha^2 D(s)^2 \sigma \left[1 - \sigma \ln\left(1 + \overline{r}^{SB}\right)\right] \right\}. \tag{42}$$

Rewriting the above partial derivative, we can obtain the first point of Proposition 2.

We can analogously obtain the second point. □

Data Availability

This study is a theoretical research and does not involve any data.

Disclosure

An older version of this manuscript is titled "Contract design for EU Air Traffic Delay Reduction" [44].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors gratefully acknowledge the assistance of Anming Zhang, Achim Czerny, Nicole Adler, Christian Bontemps, Doh-Shin Jeon, Yassine Lefouili, Natalia Fabra, Michele Polo, Franck Fichert, Kenneth Button, Radosav Jovanovi¢, conference participants, and the reviewers for their insightful comments. The authors also acknowledge financial support from the National Natural Science Foundation of China (no. 72001015).

References

[1] STATFOR, *Challenges of Growth 2013*, EUROCONTROL, 2013, https://www.eurocontrol.int/publication/challenges-growth-2013.

[2] T. G. Reynolds, "Air traffic management performance assessment using flight inefficiency metrics," *Transport Policy*, vol. 34, pp. 63–74, 2014.

[3] European Union and EUROCONTROL, *European ATM Master Plan. 2015*, Publications Office of the European Union, Luxembourg, UK, 2015.

[4] M. Niklaß, B. Lührs, V. Grewe et al., "Potential to reduce the climate impact of aviation by climate restricted airspaces," *Transport Policy*, In press, 2017.

[5] N. A. Ribeiro, A. Jacquillat, A. P. Antunes, A. R. Odoni, and J. P. Pita, "An optimization approach for airport slot allocation under iata guidelines," *Transportation Research Part B: Methodological*, vol. 112, pp. 132–156, 2018.

[6] T. Blondiau, E. Delhaye, S. Proost, and N. Adler, "Acchange: building economic models to analyse the performance of air navigation service providers," *Journal of Air Transport Management*, vol. 56, pp. 19–27, 2016.

[7] V. Bilotkach, S. Gitto, R. Jovanović, J. Mueller, and E. Pels, "Cost-efficiency benchmarking of european air navigation service providers," *Transportation Research Part A: Policy and Practice*, vol. 77, pp. 50–60, 2015.

[8] K. Button and R. Neiva, "Economic efficiency of european air traffic control systems," *Journal of Transport Economics and Policy*, vol. 48, pp. 65–80, 2014.

[9] J. K. Brueckner, "Airport congestion when carriers have market power," *American Economic Review*, vol. 92, no. 5, pp. 1357–1375, 2002.

[10] J. K. Brueckner, "Internalization of airport congestion: a network analysis," *International Journal of Industrial Organization*, vol. 23, no. 7-8, pp. 599–614, 2005.

[11] J. K. Brueckner and K. Van Dender, "Atomistic congestion tolls at concentrated airports? seeking a unified view in the internalization debate," *Journal of Urban Economics*, vol. 64, no. 2, pp. 288–295, 2008.

[12] US Federal Aviation Administration, *Airport Capacity Handbook*, US Government Printing Office, Washington DC, Second ed. edition, 1969.

[13] S. A. Morrison, "The equity and efficiency of runway pricing," *Journal of Public Economics*, vol. 34, no. 1, pp. 45–60, 1987.

[14] A. Zhang and Y. Zhang, "Concession revenue and optimal airport pricing," *Transportation Research Part E: Logistics and Transportation Review*, vol. 33, no. 4, pp. 287–296, 1997.

[15] A. Zhang and Y. Zhang, "Airport charges and capacity expansion: effects of concessions and privatization," *Journal of Urban Economics*, vol. 53, no. 1, pp. 54–75, 2003.

[16] A. Zhang and Y. Zhang, "Airport capacity and congestion when carriers have market power," *Journal of Urban Economics*, vol. 60, no. 2, pp. 229–247, 2006.
[17] L. J. Basso, "Airport deregulation: effects on pricing and capacity," *International Journal of Industrial Organization*, vol. 26, no. 4, pp. 1015–1031, 2008.
[18] E. Pels and E. T. Verhoef, "The economics of airport congestion pricing," *Journal of Urban Economics*, vol. 55, no. 2, pp. 257–277, 2004.
[19] B. De Borger and K. Van Dender, "Prices, capacities and service levels in a congestible bertrand duopoly," *Journal of Urban Economics*, vol. 60, no. 2, pp. 264–283, 2006.
[20] L. J. Basso and A. Zhang, "Congestible facility rivalry in vertical structures," *Journal of Urban Economics*, vol. 61, no. 2, pp. 218–237, 2007.
[21] H. Yang and A. Zhang, "Price-cap regulation of congested airports," *Journal of Regulatory Economics*, vol. 39, no. 3, pp. 293–312, 2011.
[22] H. Yang and A. Zhang, "Impact of regulation on transport infrastructure capacity and service quality," *Journal of Transport Economics and Policy (JTEP)*, vol. 46, pp. 415–430, 2012.
[23] D. Gillen and B. Mantin, "The importance of concession revenues in the privatization of airports," *Transportation Research Part E: Logistics and Transportation Review*, vol. 68, pp. 164–177, 2014.
[24] A. Cook and G. Tanner, "European airline delay cost reference values, for EUROCONTROL performance review unit," Technical Report, University of Westminster, London, England, 2011.
[25] B. Caillaud, R. Guesnerie, P. Rey, and J. Tirole, "Government intervention in production and incentives theory: a review of recent contributions," *The RAND Journal of Economics*, vol. 19, no. 1, pp. 1–26, 1988.
[26] D. P. Baron and R. B. Myerson, "Regulating a monopolist with unknown costs," *Econometrica*, vol. 50, no. 4, pp. 911–930, 1982.
[27] D. P. Baron and D. Besanko, "Regulation, asymmetric information, and auditing," *The RAND Journal of Economics*, vol. 15, no. 4, pp. 447–470, 1984.
[28] J.-J. Laffont and J. Tirole, "Using cost observation to regulate firms," *Journal of Political Economy*, vol. 94, no. 3, Part 1, pp. 614–641, 1986.
[29] J. K. Brueckner, "Network structure and airline scheduling," *Journal of Industrial Economics*, vol. 52, no. 2, pp. 291–312, 2004.
[30] J. K. Brueckner and R. Flores-Fillol, "Airline schedule competition," *Review of Industrial Organization*, vol. 30, no. 3, pp. 161–177, 2007.
[31] R. Flores-Fillol, "Airline competition and network structure," *Transportation Research Part B: Methodological*, vol. 43, no. 10, pp. 966–983, 2009.
[32] R. Flores-Fillol, "Congested hubs," *Transportation Research Part B: Methodological*, vol. 44, no. 3, pp. 358–370, 2010.
[33] A. Dixit, "A model of duopoly suggesting a theory of entry barriers," *The Bell Journal of Economics*, vol. 10, no. 1, pp. 20–32, 1979.
[34] O. Richard, "Flight frequency and mergers in airline markets," *International Journal of Industrial Organization*, vol. 21, no. 6, pp. 907–922, 2003.
[35] X. Fu, M. Lijesen, and T. H. Oum, "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 (JTEP)*, vol. 40, pp. 425–447, 2006.
[36] M. H. Lin, "Airlines-within-airlines strategies and existence of low-cost carriers," *Transportation Research Part E: Logistics and Transportation Review*, vol. 48, no. 3, pp. 637–651, 2012.
[37] M. H. Lin, "Airline network competition with new brand subsidiaries," *Journal of Transport Economics and Policy (JTEP)*, vol. 49, pp. 58–78, 2015.
[38] C. Jiang and A. Zhang, "Effects of high-speed rail and airline cooperation under hub airport capacity constraint," *Transportation Research Part B: Methodological*, vol. 60, pp. 33–49, 2014.
[39] T. D'Alfonso, C. Jiang, and V. Bracaglia, "Would competition between air transport and high-speed rail benefit environment and social welfare?" *Transportation Research Part B: Methodological*, vol. 74, pp. 118–137, 2015.
[40] C. Wang and X. Wang, "Airport congestion delays and airline networks," *Transportation Research Part E: Logistics and Transportation Review*, vol. 122, pp. 328–349, 2019a.
[41] C. Wang and X. Wang, "Why do airlines prefer multi-hub networks?" *Transportation Research Part E: Logistics and Transportation Review*, vol. 124, pp. 56–74, 2019.
[42] University of Westminster, "The cost of passenger delay to airlines in europe—consultation document," Technical Report, University of Westminster, London, UK, 2015.
[43] D. Robyn, *Air Support: Creating a Safer and More Reliable Air Traffic Control System*, The Brookings Institution Discussion Paper 2008-11, 2008.
[44] E. Malavolti and C. Wang, "Contract design for EU air traffic delay reduction," 2020, https://tel.archives-ouvertes.fr/tel-02555753/file/Estelle.Malavolti.pdf.